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Advances in Window Technology: 1973-1993

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ABSTRACT

Until the 1970s, the thermal performance of windows and other fenestration technologies was rarely of interest to manufacturers, designers, and scientists. Since then, however, a significant research and industry effort has focused on better understanding window thermal and optical behavior, how windows influence building energy patterns, and on the development of advanced products. This chapter explains how fenestration technologies can make a positive impact on building energy flows, what physical phenomena govern window heat and light transfer, what new products have been developed, and what new products are currently the subject of international research efforts.

7.1 Introduction and Background

Windows and other fenestration products are at the foundation of good architectural design. They serve many functions in a building: aesthetic, psychological, structural, ventilation, and egress. Windows can also have an extremely significant impact on a building's energy use. Proper placement and utilization of fenestration components in any building can reduce the building's energy use to below that of a similar building without any windows; improper use of fenestration products can have a catastrophic effect on energy use patterns and thermal comfort.

In 1973, when Americans as a whole first began to consider the effects of energy consumption in buildings, the energy impacts of windows were regarded as a "fact of life"; something which HVAC equipment was designed for. Most of the engineering knowledge in the area of windows and heat transfer focused on sizing HVAC systems to meet the energy loads imposed on buildings by windows during cold nights or hot sunny days. However, following the energy crisis of 1973, there were two reactions to the new-found realization that windows were responsible for a large fraction of the country's energy use (estimated at 5% of all the energy used in the US (Frost, 1993) or the equivalent of the energy produced by the Alaska pipeline). One reaction was to design buildings with smaller windows and board up windows in existing buildings. The other reaction was to accelerate research into window heat transfer and optics, working towards redesigning window products so that one day, the energy impact of windows can be viewed as an asset and not a liability. This chapter summarizes what has been learned about the energy impacts of windows in buildings, what has been done to develop new products, and what new products remain to be developed.

7.2 Potentials for Energy Efficient Windows

While most windows in buildings today have a negative impact on a building's energy load, there exists the technological potential for windows to be designed which, for any building type in virtually any continental US climate, could make a positive contribution to the building's annual energy load. This section illustrates how, conceptually, windows in different applications can act to have a positive impact on building energy flows. Specific techniques for achieving this are discussed in subsequent sections. Significant advances have been made during the past two decades in turning some of these potentials into cost-effective products; others remain as a challenge for the future.

For residential buildings in heating dominated climates, windows must be designed such that the solar gains which pass through the windows are greater than the energy losses through a window. This concept is at the cornerstone of basic passive solar design where windows are oriented to the south to admit more solar radiation than the energy they lose. However, while south orientations provide the maximum amount of solar radiation, there is still solar radiation coming from all other orientations. If the window is a good enough insulator, only a small amount of solar radiation is required to offset the heat losses. This is illustrated in Fig. 7.1 (Sullivan 1991, Sullivan 1987, Arasteh 1989b)

Windows with properties on these lines will gain as much useful passive solar heat as they will lose in conductive/convective/radiative losses during

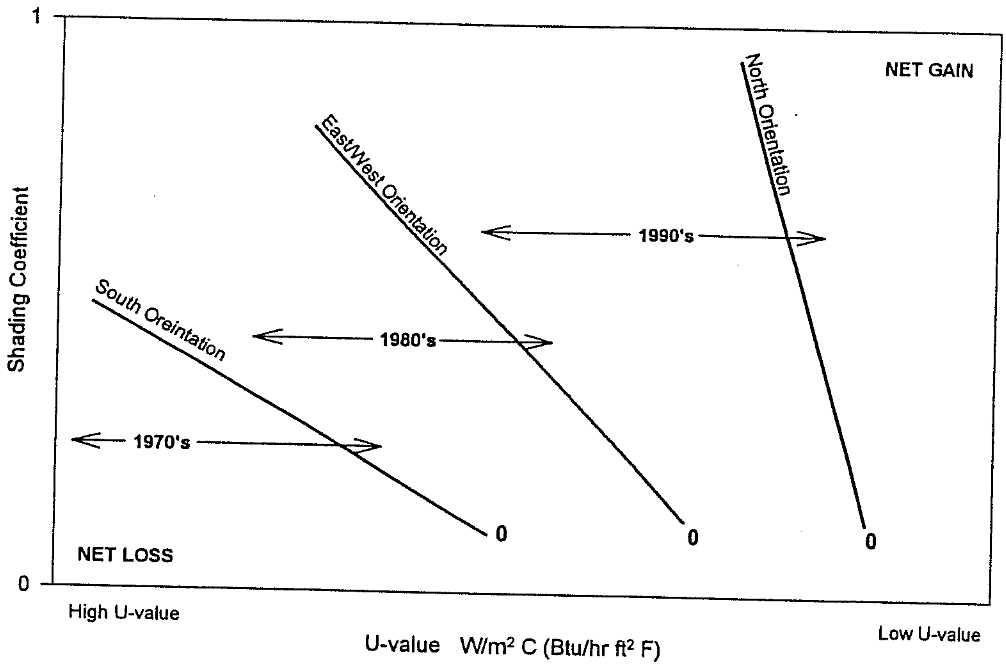


Figure 7.1: Schematic lines of zero net annual energy flux for typical northern US climates as a function of U-value and Shading Coefficient.

the heating season. Windows to the right of the lines will be net energy gainers.

For residential buildings in cooling dominated climates, solar gains through windows typically must be offset by cooling the building. In such cases, solar transmission is only needed when the occupants are in the room. The only solar radiation required is that which stimulates the human eye (often a small portion of the solar spectrum). Thus, with advanced window designs, solar loads can be reduced by an order of magnitude without impacting the function of a window. Note that in virtually all cooling load dominated climates in the continental US, heating loads, while minor, still exist. As discussed in the above paragraph, windows could be used as a passive solar element to trap these gains.

Commercial buildings in virtually all climates typically suffer from an abundance of solar gains which lead to high cooling loads. However, by filtering out unnecessary solar radiation (by magnitude and wavelength), by redirecting incoming daylight into the space so that it can be used effectively to offset electrical lighting needs, and by utilizing daylighting sensors and

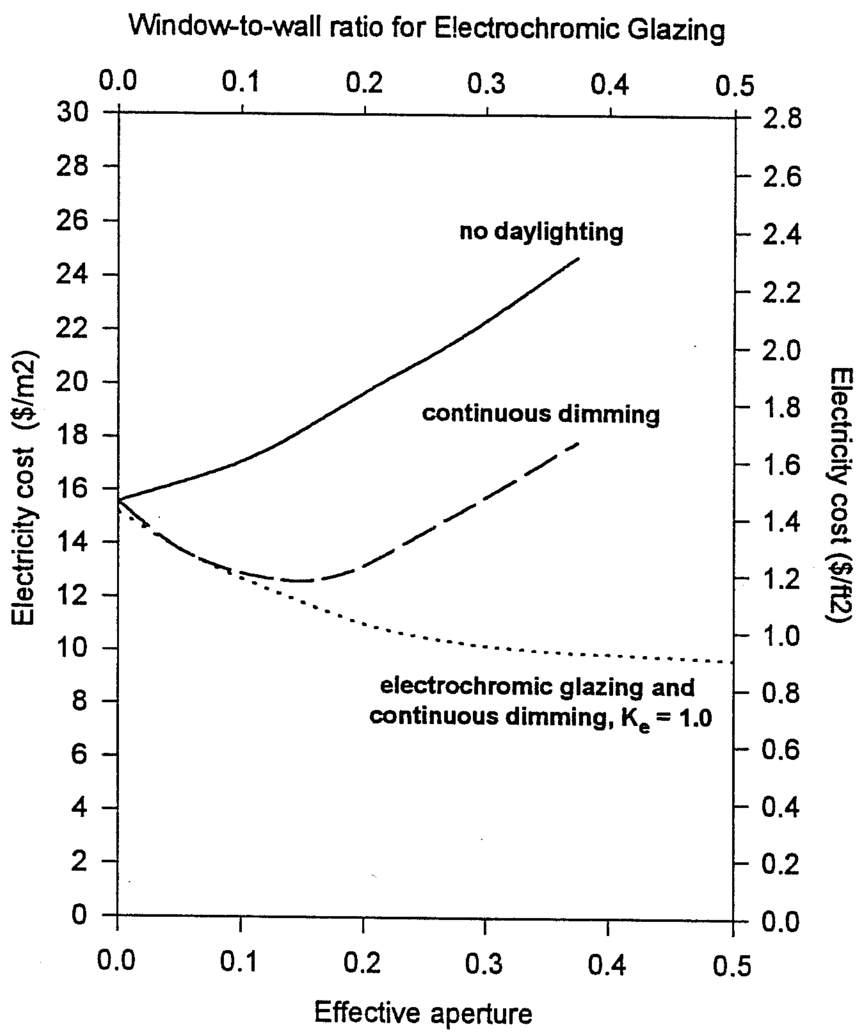


Figure 7.2: Representative electricity costs as a function of aperture area for the perimeter zone in a typical office building in the mid-western U.S.

lighting controls to appropriately dim electric lights, commercial building fenestration elements can make a positive contribution to a building's energy use. Fig. 7.2 shows the results of total commercial building simulation studies designed to assess the impacts of existing and proposed fenestration technologies on building energy use.

The "no daylighting" case assumes a standard lighting power density (1.5 W/ft^2) and no dimming of the electric lights in response to available daylight. Adding continuous dimming daylighting controls to the lighting system reduces lighting and cooling costs until solar gains saturate the space. The addition of an electrochromic glazing to the system allows excessive solar gains to be rejected during periods of high solar radiation while still allowing the aperture to admit as much solar radiation as possible during periods of low daylight availability.

7.3 Heat Transfer and Optics of Window Systems

In order to understand the design of new window products, it is first necessary to understand the heat transfer and optics of window systems. This will better enable the reader to understand the significance of new components and total products.

For many years, total window heat transfer indices were assumed to be those of the glazed areas alone. Recently, with the advent of more advanced glazings, the role of frame and edge effects has become more significant. Therefore, window heat transfer indices should always be thought of as representing the performance of the total window. The following total window heat transfer, optical, and related properties are typically used in this field:

U-value: the total heat transfer coefficient of the window system (in W/m^2-C or Btu/hr-ft^2-F) which includes conductive, convective, and radiative heat transfer. The inverse of the U-value is the R-value, or resistance to heat transfer.

SHGC: the solar heat gain coefficient of the total window system represents the solar heat gain through the window system relative to the incident solar radiation. Although SHGCs can be determined for any angle of incidence, the default and most commonly used reference is normal incidence solar radiation.

SC: the shading coefficient for the total window system represents the ratio of solar heat gain through the window system relative to that through 3mm (1/8") clear glass at normal incidence.

VT: the total window system's transmittance across the visible portion of the solar spectrum. Although VTs can be determined for any angle of incidence, the default and most commonly used reference is normal incidence solar radiation.

Infiltration rate: the rate at which air moves through the window system, due to pressure and temperature induced pressure differences between the inside and outside of the window. Infiltration rates are expressed in air flow rates (m^3/hr or cfm).

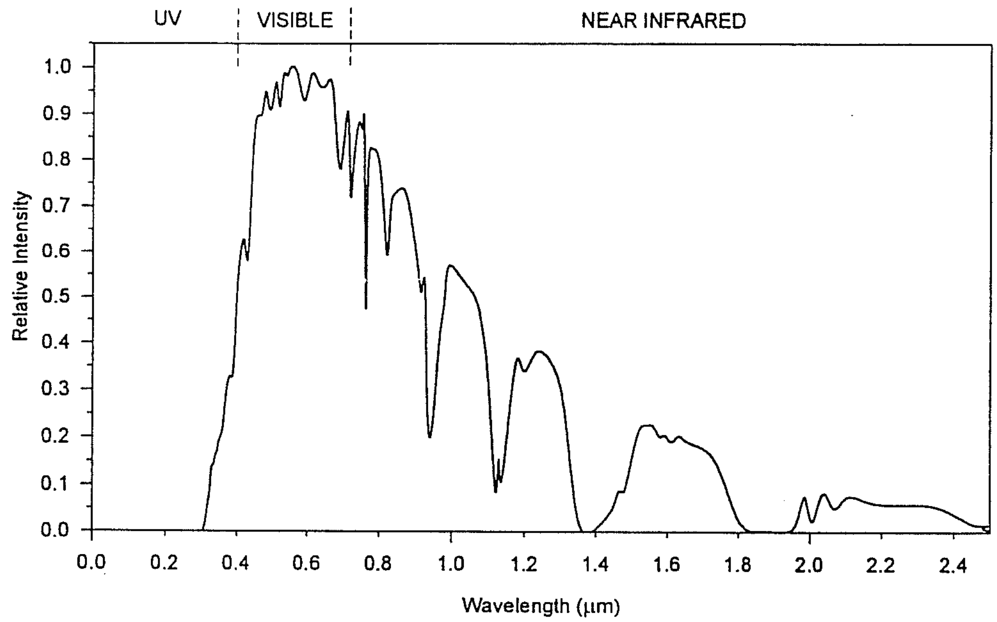


Figure 7.3: The solar spectrum as a function of wavelength.

An individual glazing layer and systems of glazing layers have various optical properties. These are discussed in Section 7.3.2.

Heat transfer through windows is best broken down into two separate subject areas: heat transfer through the center-of-glass glazed areas and heat transfer through window frame and edge areas (includes glazed areas near the frame affected by two-dimensional thermal bridging). These subcategories of heat transfer are listed below and discussed in the following sections:

- Conductive, convective, and radiative effects through glazed areas
- Solar heat gain and optical properties of glazed areas
- Conductive, convective, and radiative effects through frame and edge areas
- Solar heat gain through frame areas
- Infiltration through frames.

It is also important to understand the environmental effects which influence window heat transfer and optics. These are:

- the solar spectrum (see Fig. 7.3);
- interior and exterior air and radiative temperatures;
- exterior wind speed and direction;

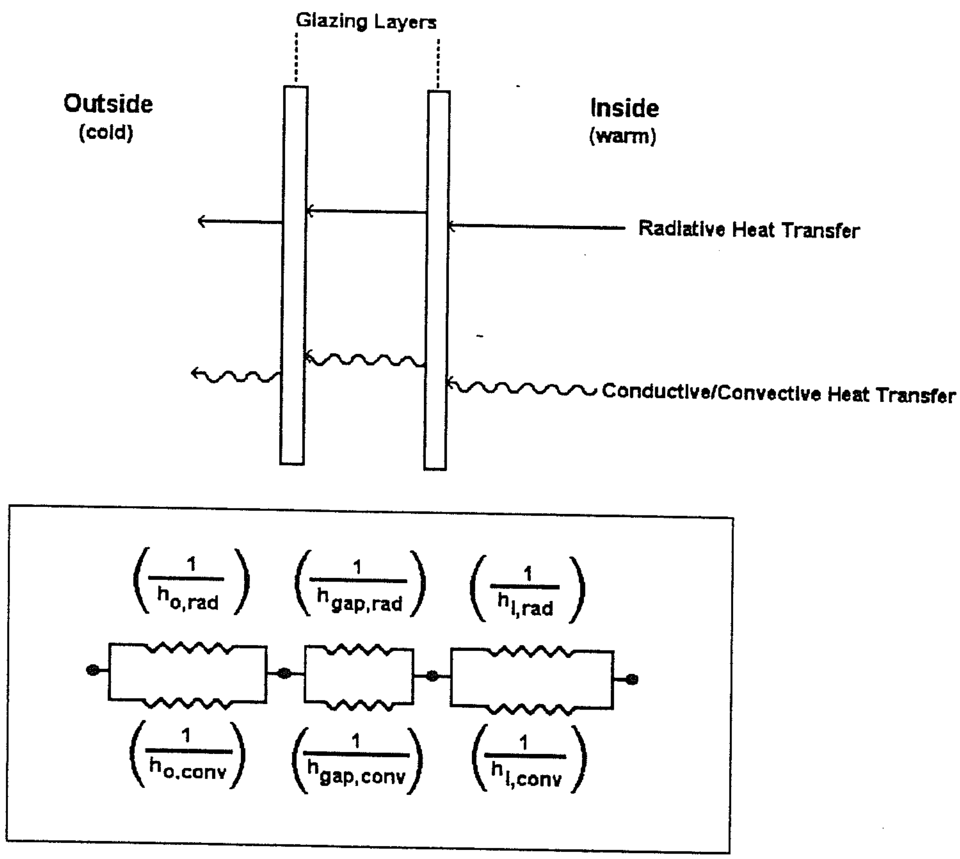


Figure 7.4: Modes of heat transfer through a window and an electrical analog.

- forced air flow inside the building.

7.3.1 Conductive, convective, and radiative effects through glazed areas

Glazing systems are affected by all modes of heat transfer. This is illustrated for a generic double glazed window system in Fig. 7.4.

In most window systems, the glazing layers contribute very little towards the overall resistance to heat transfer. Table 7.1 gives the conductivites of common glazing materials, and, for comparison, that of air. In addition, for glass and most other glazing materials, the long-wave radiative transmittance (tir) is 0. As a result, the glazing system heat transfer can be analyzed to a high degree of accuracy by breaking down the glazing system into an assembly of nodes (where each glazing layer is a node) and calculating the

Table 7.1: Thermal Conductivities

	W/m-C	(Btu-in/hr-ft2-F)
Glass	0.90	6.2
Acrylic	0.19	1.3
Polycarbonate	0.19	1.3
Air	0.024	0.17

heat transfer between nodes using first principles (for radiative effects) or empirical relationships (for conductive/convective effects).

Generally; there are a limited number of relationships used to analyze convective/conductive heat transfer:

The interior film coefficient (h_i) provides the majority of the resistance in a single glazed window. As the glazing system's resistance increases, the value of the interior film coefficient stays approximately the same and thus its impact on the total glazing system decreases. Interior film coefficients are a function of the temperature difference between the glass surface and the interior air as well as the emittance of the glass surface. Generally, the assumption is that the room is effectively a black body and that there is only natural (and no forced) convection on the interior surface. Forced convection (i.e. from HVAC equipment) will increase the film coefficient significantly (ASHRAE 1993). With these assumptions, the interior conductive/convective film coefficient (h_{ic}) can be expressed as (ASHRAE 1993):

$$h_{ic} = A(\Delta T)^{0.25},$$

where A is 1.77 for SI units (W/m^2-C) and 0.27 for IP units (Btu/hr-ft^2-F).

Under typical conditions, h_{ic} is approximately 8 W/m^2-C (1.4 Btu/hr-ft^2-F). The values given above and typically used, assume vertical glazing; values will be different for tilted glazings (Finlayson 1993).

Exterior film coefficients (h_o) typically provide much less resistance to heat transfer than interior film coefficients. This is due to the fact that exterior film coefficients are affected by exterior winds. The radiative effect is typically outweighed by wind driven convective effects. (However, if there is no wind and the sky is clear, leading to an effective lower sky radiative temperature, radiative effects can dominate.) Historically, the HVAC and window industries have assumed a wind speed of 6.7 m/s (15 mph) for winter conditions and 3.3 m/s (7.5 mph) for summer conditions which lead to high values of h_o, approximately 25 W/m^2-C (4.4 Btu/hr-ft^2-F) and 17 W/m^2-C (3.0 Btu/hr-ft^2-F) for winter and summer respectively. For the purposes of sizing HVAC equipment, these values are reasonable. For purposes of determining annual energy effects, these values are typically modified by expressions for h_o as a function of exterior wind speed (Yazdanian 1994). The values given above and typically used, assume vertical glazing; the effect on tilt (assuming a wind) are minimal (Shakerin 1987).

Of most interest to those concerned with window heat transfer issues are conductive/convective and radiative effects between glazing layers. Numerous experimental studies have examined conductive/convective effects between parallel glazing layers (El Sherbiny 1982). Conductive/convective heat transfer within a glazing cavity is a function of:

- the temperatures on both boundary surfaces;
- the gas thermophysical properties
  - . thermal conductivity (λ)
  - . viscosity (μ)
  - . density (ρ)
  - . Prandtl number (Pr);
- the gap width (w);
- the gap height (h).

The gap conductive/convective heat transfer coefficient (h_c) is given by

$$h_c = \frac{\lambda}{w} \cdot \mathrm{Nu}$$

where Nu, the Nussalt number, is given by (ElSherbiny 1982):

$$\mathrm{Nu} = \left[1 + \left(0.0303\mathrm{Ra}^{0.402}\right)^{11}\right]^{0.091}$$

where Ra, the Rayleigh number is the product of the listed Prandtl number and the Grashoff number (Gr). The Grashoff number is defined by:

$$\mathrm{Gr} = \frac{g\beta\rho^2 w^3 \Delta T}{\mu^2}$$

where g is gravitational acceleration (9.8 m/s^2); β is the coefficient of thermal expansion and is approximated by the inverse of the mean absolute temperature; and ΔT is the temperature difference between the glazing layers.

The correlation given above assumes vertical glazing and must be modified for tilted glazing systems (Finlayson 1993).

Radiative exchange between glazing layers is calculated using the Stephan-Boltzmann law using the surface infrared hemispherical emissivity and surface temperature (Finlayson 1993). Virtually all gasses used between glazing layers are non-absorbing in the infrared; as a result the conductive/convective effects between glazing layers and the radiative effects between glazing layers can be treated as parallel paths with a high degree of accuracy. For a discussion of infrared absorbing gasses between glazing layers see Reilly 1990.

Computer models have been developed (Windows and Daylighting Group 1992, Finlayson 1994, Wright 1993) which, using the above procedure, and assuming steady state conditions, can be used to analyze the total glazing system heat transfer. These programs iterate to determine steady state temperatures such that, at each node, the net energy flux entering each node is the same as that leaving each node. Heat transfer rates between nodes, and thus for the total system, can now be evaluated with the final temperatures.

7.3.2 Solar heat gain and optical properties of glazed areas

In order to understand solar heat gain through a window it is first necessary to understand the optical properties of individual layers as well as of a system of glazing layers. We first consider the case of specular glazing layers (i.e. glass, many plastics) where the glazing's transmittance and reflectance (see Fig. 7.5) are measured as a function of angle of incidence and wavelength (λ) in a spectrophotometer (ASTM 1988). For a specific angle of incidence and assuming unpolarized light, layer transmittance and reflectance are measured over the range of the solar spectrum as a function of wavelength. For each spectral property, $P(\lambda)$, the following individual properties are defined:
P_s, the total solar property:

$$P_s = \int P(\lambda)E_s(\lambda)d\lambda$$

P_v, the total visible property:

$$P_v = \int P(\lambda)E_s(\lambda)R(\lambda)d\lambda$$

P_{uv}, the damage-corrected "ultraviolet" property:

$$P_{uv} = \int P(\lambda)E_s(\lambda)D(\lambda)d\lambda$$

where $E_s(\lambda)$ is the solar spectral irradiance function (see Fig. 7.3), $R(\lambda)$ is the photopic response of the eye (IES 1972), and $D(\lambda)$ is a damage weighting function (Krochman 1983).

The overall properties of a system of multiple layers are computed from the properties of individual layers using recursive relationships and depend on the properties of all the individual layers within the system (Finlayson 1993). It is important that this calculation be performed as a function of wavelength before integrating over the wavelength range of interest.

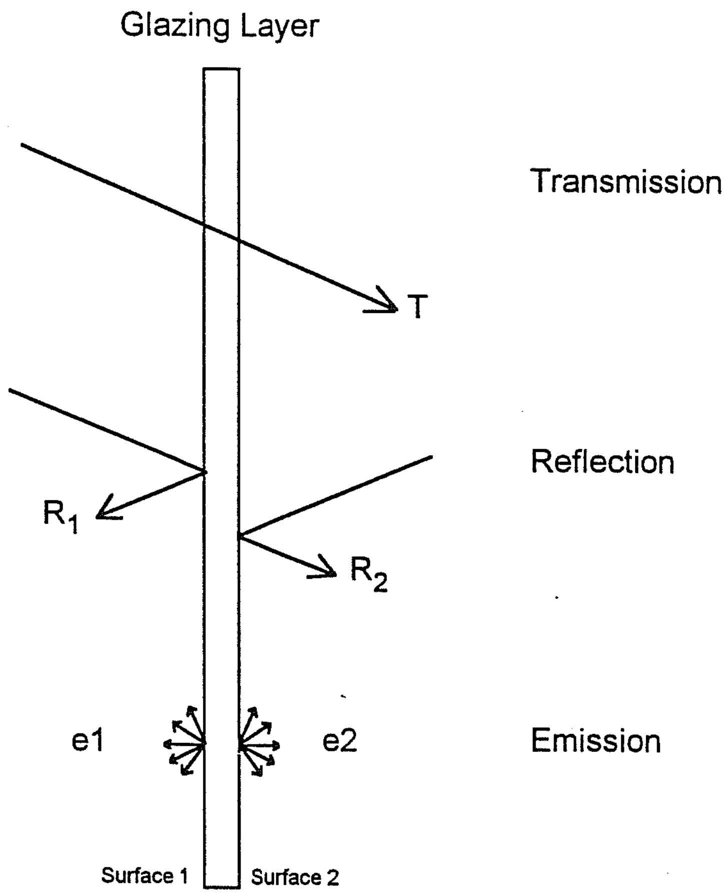


Figure 7.5: Solar spectrum transmittance and reflectance of specular glazings; long wave emittance.

For non-specular or diffuse layers, solar spectrum properties must be defined for a given angle of incidence and a given exiting angle. As shown in Fig. 7.6, incident and exiting angles can be either collated or hemispherical (Papamichael 1987). Measuring these properties for a non-specular layer or system of layers which include at least one non-specular layer is a more involved process; measurements must be made through the use of a scanning radiometer or an integrating sphere. A procedure to determine the solar properties of non-specular layers, based on the properties of individual layers,

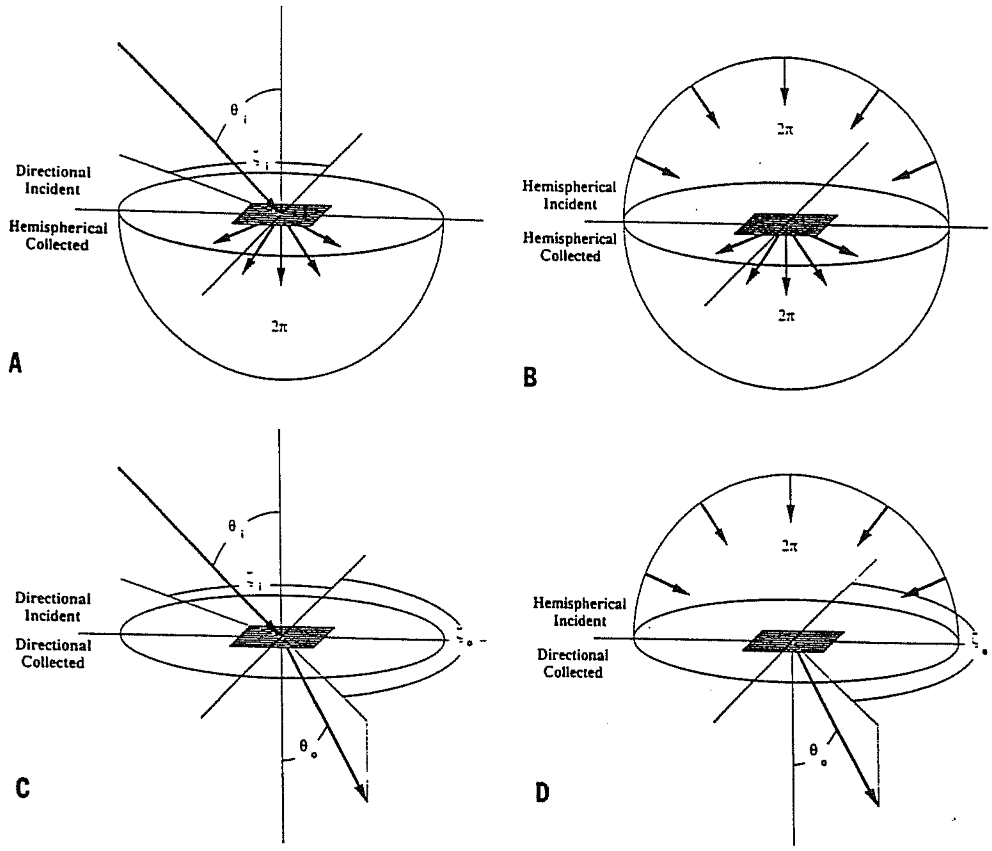


Figure 7.6: The concepts of (A) directional-hemispherical, (B) bi-hemispherical, (C) bi-directional, and (D) hemispherical-directional transmittances.

has been developed (Papamichael 1988). The use of ray-tracing computer programs provides an alternative approach (Kim 1986).

7.3.3 Conductive, convective, and radiative effects through frame and edge areas

Window frames can contain many different materials, typically solids or small enclosed air spaces, with significantly different thermal conductivities. As a result, frame heat transfer is best examined through the use of two or three dimensional heat transfer modeling tools (i.e. Finite Element Analysis, Finite Difference, or Finite Volume) (Carpenter 1993). These tools typically compute temperatures, isotherms, and total heat flows.

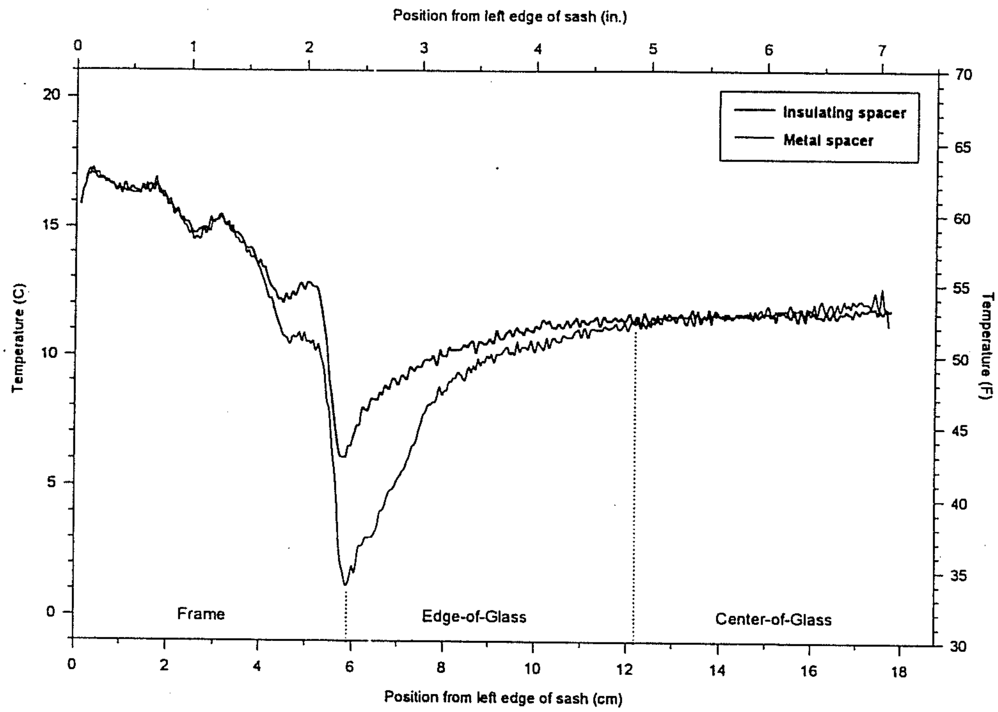


Figure 7.7: Warm side window surface temperatures for a typical residential window generated using an infrared imaging system. The window is subjected to a temperature difference in order to simulate winter conditions. The spacer used to separate the glazing layers is a significant thermal bridge, as shown by the cold temperatures at the interface between the frame and edge-of-glass regions.

The analysis of the effects of a two-dimensional and three-dimensional heat transfer through a window frame must not be limited to the frame area alone. Because high conductivity metal spacers (recessed below the sightline into the frame) are typically used to separate glazing layers, thermal short circuits are created at the edge-of-glass area. Typically, the limits of this effect are found within 63mm (2.5 in.) of the window's sightline (see Fig. 7.7).

Some windows utilize wood, metal, or other elements to create either the look of or actual divided-lites. In many of these cases, the thermal bridging effects can be significant and must be considered in evaluating window thermal performance.

7.3.4 Solar heat gain through frame areas

The solar heat gain effects of a window frame are a function of the frame's solar absorptance and the resistance to heat transfer from the outside surface to the inside air. With the exception of dark aluminum or steel frames, these effects are virtually negligible.

7.3.5 Infiltration through frames

Air flow (or infiltration) through windows can be a significant mode of heat transfer. Infiltration is generally a function of operator type (i.e. fixed or opening, and type of the opening mechanism), weatherstripping material, frame construction, and installation practice. Infiltration rates are measured in laboratory tests (ASTM 1992), do not include the effects of installation or product durability, and are expressed in m^3/hr or cfm for a given pressure difference.

The actual infiltration rate under non-test conditions depends on the building, wind and temperature conditions, surrounding obstructions, and installation practices. Infiltration rates measured under test conditions must be modified to determine the actual infiltration rate for the given conditions (Klems 1983).

7.4 Technological Advances in Reducing Window Heat Losses

A major thrust in developing energy-efficient windows over the past two decades has revolved around the design of products with lower U-values. In addition to the obvious benefits of lower heating (and often lower cooling) loads, lower U-value windows result in interior surface temperatures closer to ambient air temperatures; this results in a more comfortable interior environment (ASHRAE 1981) year around and significantly reduced condensation on the interior surface of the windows during the heating season.

Efforts in the 1970's and early 1980's to produce highly insulating window products revolved around using existing technologies. Thus, triple and quadruple glazed windows began to appear on the market; such products produced lower U-values by increasing the number of still air spaces. While each layer added a resistance of approximately 1 hr-ft^2-F/Btu to the window system, the added layers also increased the weight of the unit, the cost of fabrication, and lowered the solar transmittance significantly (Selkowitz 1979).

7.4.1 Reducing Radiative Heat Transfer

In the mid 1970's it became clear that most of the heat transfer through a typical double glazed window was through infrared radiation exchange from one layer to another (see section 7.3.1) This is illustrated in Fig. 7.8a. While glass blocks the direct transmittance of long-wave infrared radiation,

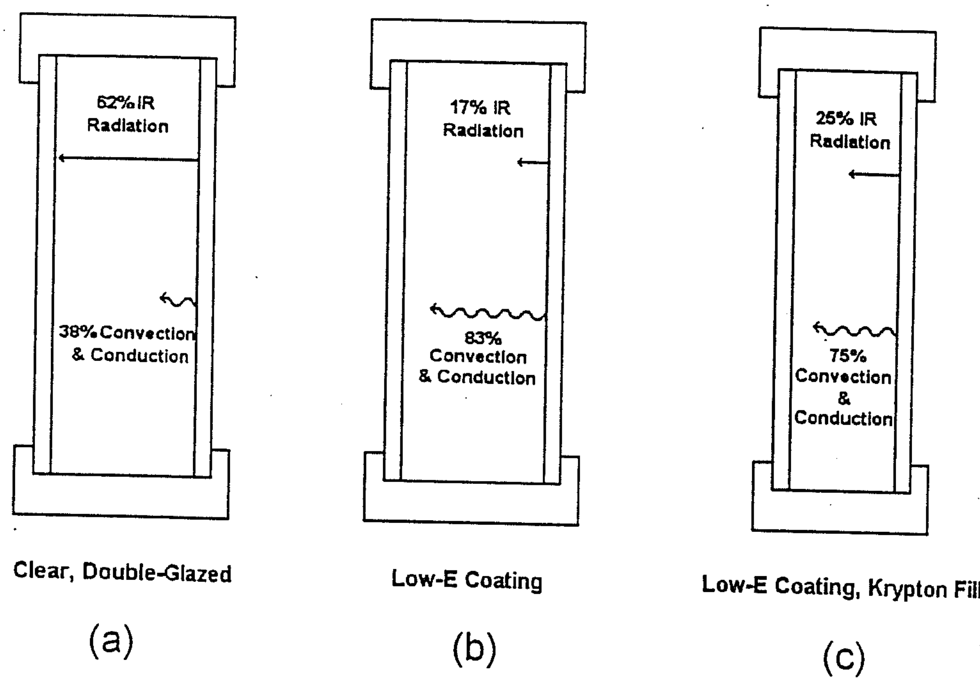


Figure 7.8: Radiative and conductive heat transfer in typical double glazed windows.

its emittance is high (0.84), thus absorbing the radiation and re-emitting it at a high rate.

Radiative heat transfer across a gap is proportional to the gap's effective emittance given by:

$$E = \frac{1}{1/e_1 + 1/e_2 - 1}$$

where e_1 and e_2 are the hemispherical longwave emissivities of facing glazing surfaces. Reducing the emittance on any one surface would greatly reduce radiative heat transfer (see Fig. 7.8b). In the mid 1970's, the US DOE contracted through LBL to a small company (Suntek, now Southwall) to develop a transparent, optically clear low-emissivity coating which could be used in window applications. Previous to this time, most low-emissivity coatings in existence for window products had high reflectances in the visible portion of the spectrum and did not have low enough emittances. The challenge, therefore, was to produce a coating which had a transmittance which resembled that of glass throughout the solar spectrum but which had

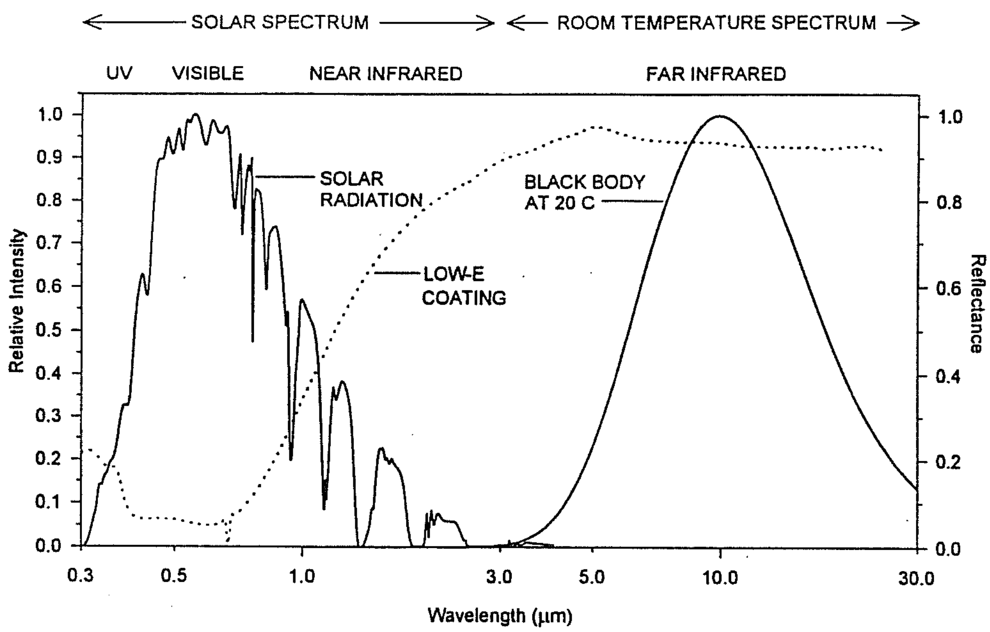


Figure 7.9: The reflectance of a typical low-emissivity coating superimposed over the solar spectrum and the spectrum of a black-body at room temperature.

a high reflectance (low-emittance) throughout the infrared portion of the spectrum (see Fig. 7.9).

In 1983, Southwall began to offer their first Heat Mirror™ product, a thin polyester film with a silver based coating (emittance approximately 0.15). The coating was applied with a roll coater to the polyester film substrate because of the difficulty then in coating large pieces of glass. This product required the polyester substrate to be suspended between the two glazing layers; a techniques which had the benefit of creating a second air space but at a higher fabrication cost.

Southwall's creation of a product which cut heat loss rates by 50% sparked an interest in developing large scale glass coaters. Two types of coating processes, sputtered and pyrolitic, were developed in the 1980's in order to produce large-volumes of quality low-emissivity coated glass at a high rate. Pyrolitic coatings are incorporated into the float glass production process and tend to produce coatings which are more durable. They also tend to have higher solar transmittances and slightly higher emissivities. Sputtered systems (see Fig. 7.10) apply a coating through a stand-alone vacuum deposition process. These coatings often need to be handled with care but have lower emissivities.

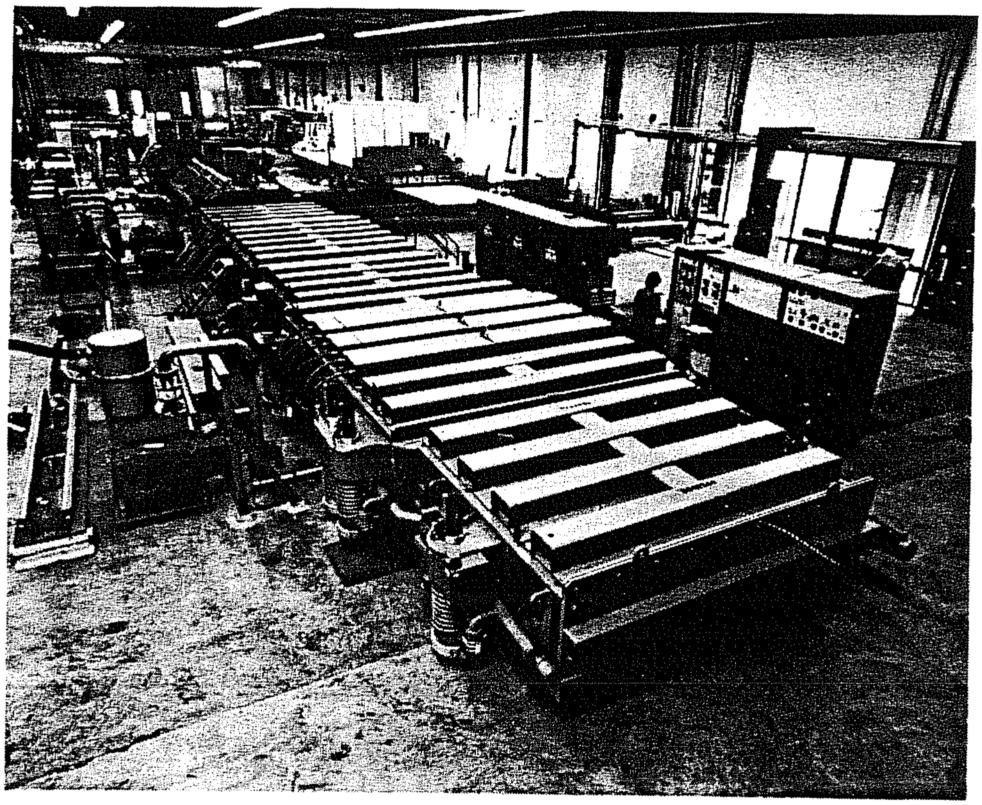


Figure 7.10: Vacuum chambers are used in the production of sputtered low-emissivity glass.

7.4.2 Reducing Conductive/Convective Heat Transfer

The use of a low-emissivity coating (low-e) can reduce heat transfer across a gap by a factor of five to ten. At this point, as shown in Fig. 7.8c, heat transfer across a gap is dominated by conduction and natural convection. While air is a relatively good insulator, there are other gasses with lower thermal conductivities. As discussed in Section 7.3.1, lower thermal conductivities are important in minimizing conduction while higher viscosities are necessary in order to limit convection. Since gasses used in a window must be both cost-effective and pass health and safety criteria, the list of potential gasses for use in windows is limited to those in the Table 7.2. Note that the recent phase-out of CFC's, an impending phase-out of HCFC's, and a desire not to promote greenhouse warming gasses such as SF6 limits this list even

Table 7.2: Gasses suitable for use in insulating glass units.

Gas	Thermal conductivity Btu/hr-ft-F	W/m-C
Air	0.0139	0.241
Argon	0.0094	0.0162
CO2	0.0084	0.0146
Krypton	0.0050	0.0086

further. Furthermore, gasses such as Krypton with low conductivities, unfortunately have low viscosities. As a result, as shown in Fig. 7.11, there are practical limits to the performance potentials which can be achieved across a given gap (Arasteh 1985). Gas retention is a strong function of the sealant type and quality control; properly manufactured units have been shown to have gas loss leakage rates of less than 1% per year.

7.4.3 High Performance Insulating Glass Units

By the late 1980's, many manufacturers were offering double glazed units designed to take advantage of the availability of low-emissivity coating and cheap gas-fills such as argon. Such units typically had center-of-glass U-values in the 0.25 – 0.35 Btu/hr-ft^2-F range.

Improvements from extra low-conductivity gasses such as Krypton, however, come from their use in multiple layer units with small gap-widths. Large gap width insulating glass units (over 1" in width) tend to pose manufacturing difficulties; the performance of a 1" wide insulating glass unit could therefore be maximized by creating a three layer unit with two gas gaps (each approximately 1/4"-3/8" wide) and with each gap utilizing a low-e coating to reduce radiative heat transfer (see Fig. 7.12). Center-of-glass U-values for such units fell to below 0.20 and as low as 0.10 with exceptional low-emissivity coatings (Arasteh 1989a. Arasteh 1989b). Prototype windows using three-layer high performance units were built and tested as part of an LBL research project from 1988-1991; lab and field tests confirmed product performance potential (see Fig. 7.13). Commercial products using these concepts emerged in 1991.

7.4.4 High Performance Window Products

While the late 1980's saw significant improvements to center-of-glass technology, few changes were made to the basic materials used to manufacture windows. Thus, the fraction of heat lost through the frame in a typical window increased and the relative thermal bridging effects of frame components increased. Table 7.3 (ASHRAE 1989) shows total window U-values for standard frame types with conventional insulating glass units and

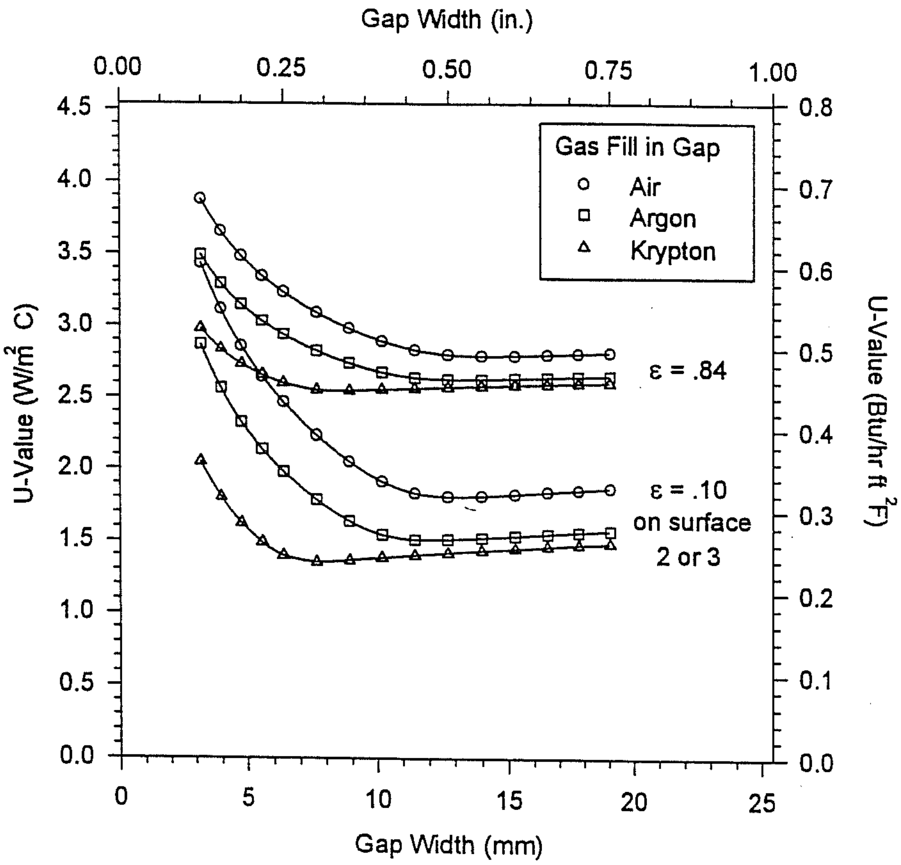


Figure 7.11: The U-value of the glazed area of a window will change with gap-width, gas-fill, and surface emissivities. Data is given for a double glazed window with glazing surfaces numbered from the outside in.

higher performance units. Through the use of infrared thermography, one can see the impacts of edge and frame systems on total window performance (see Fig. 7.13).

In the 1990's, attention focused on designing window products with low frame heat loss characteristics. Unlike the glass industry, window frames are made of many different materials, in many different ways, at various grades. Spacers used in the manufacture of insulated glass, typically aluminum, were also in need of a re-design. As a result, it was unlikely that there would be one or two solutions (as there was with low-emissivity coatings) which would gain a quick market share. New frame products (typically vinyl) began to

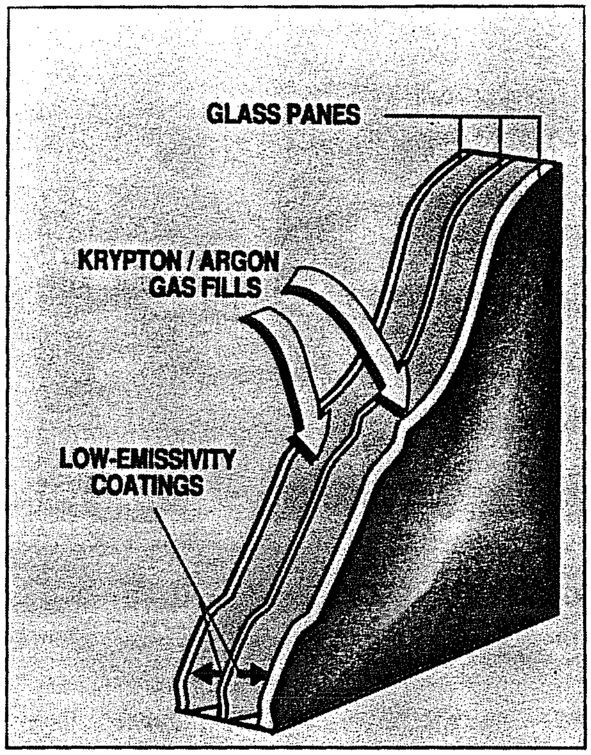


Figure 7.12: Schematic cross-section of a superwindow.

appear. Existing wood and aluminum framed products were redesigned to minimize their heat transfer effects. Vinyl window frames began to command an increasingly larger fraction of the market (Frost 1993) and began to be redesigned for optimum thermal efficiency (Beck 1992) (see Fig. 7.14). A wide variety of new spacer options including metal reinforced butyl, stainless steel, thermally broken aluminum or steel, silicone foam, and others began to appear on the market (see Fig. 7.15).

7.4.5 Reducing Infiltration Through Frames

During the 1980's, traditional "brute-force" approaches to weatherstripping were re-thought to accomplish more with less material by increasing the contact surface area (Swanson 1988). New materials, such as thermoplastic elastomers, offered additional potentials (May 1988).

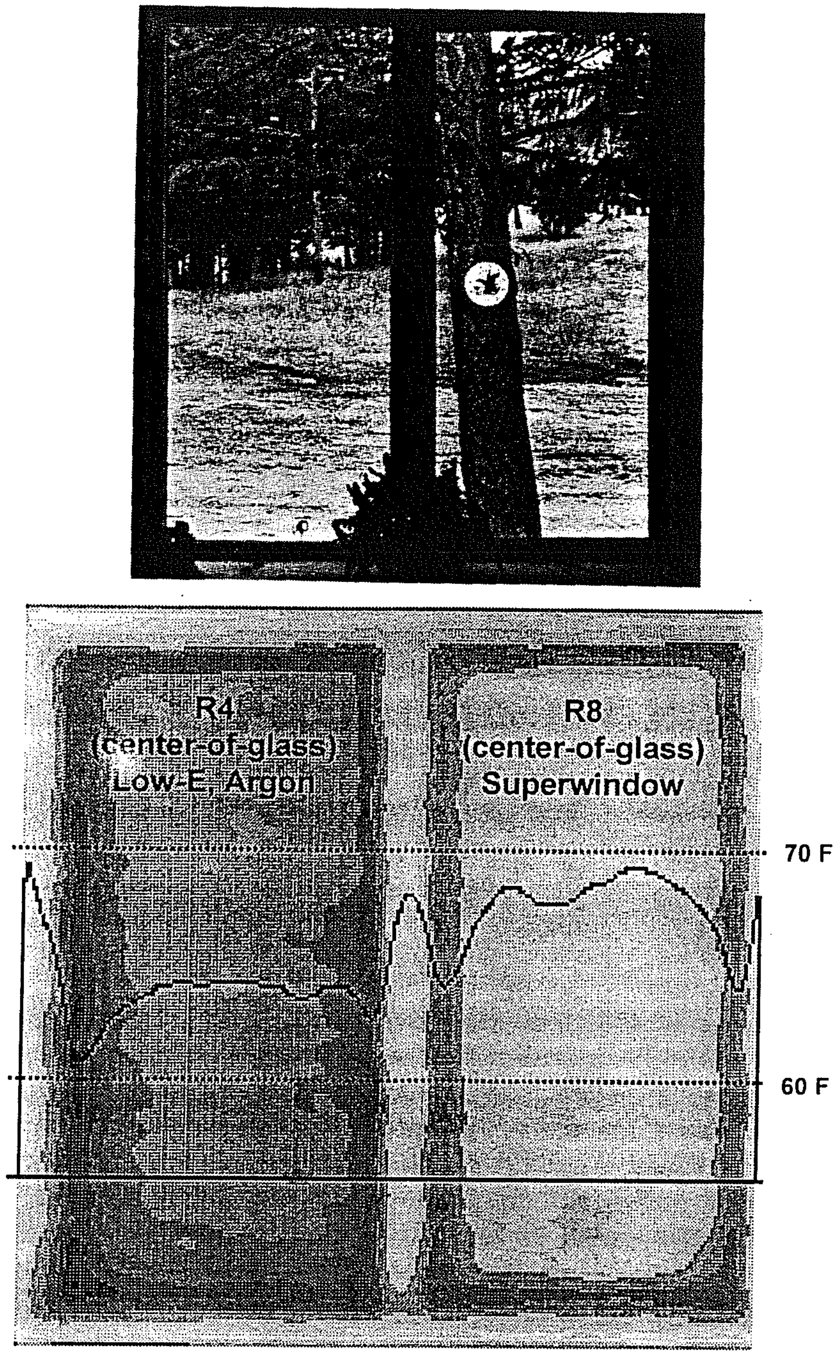


Figure 7.13: While a superwindow (right side of photo) looks just like a conventional window, IR thermography shows that its center-of-glass thermal performance is quite different. Edge effects due to thermal bridging of the spacer in this superwindow are very significant.

Table 7.3: Total Window U-values in W/m^2-C (Btu/hr-ft^2-F); typical residential size and design.

	Aluminum	Thermally Broken Aluminum	Wood/Vinyl
Standard Double	4.80 (0.85)	3.70 (0.65)	2.80 (0.50)
Double; low-e with Ar	4.25 (0.75)	2.80 (0.50)	1.70 (0.30)
Three layers; 2 low-e; Kr			1.15 (0.20)

7.4.6 Future Highly Insulating Window Technologies and Non-Conventional Products

While the above section discussed technologies which have been commercialized into mainstream manufacturing processes, several products still in research laboratories offer the potential for increased energy savings or are new approaches to controlling heat losses through building envelopes.

Referring back to sections 7.3.1 and 7.3.2, it is clear that the best gas to fill a low-e coated insulated glass unit with would be one at a very low pressure. Fig. 7.16 shows the theoretical U-value for an evacuated window as pressure drops. Evacuated windows, however, pose new technical problems for the window industry including designing a window to withstand pressure differences, safety concerns if the window should break, sealing the evacuated space, and economical production procedures. For structural reasons, small gas (i.e. 0.02 – 0.2 inches) gaps at very low pressures (10^{-7} atm) are the focus of current research efforts. At this spacing, the sealing technology becomes a critical factor and getters are required to trap gasses (i.e. helium) which diffuse through the glass. Heat transfer through spacers used to keep the glass layers apart are a significant thermal bridge through evacuated windows. Research efforts around the globe have been directed at solving these issues (Collins 1992). Fig. 7.17 shows a diagram of a proposed evacuated window (spacing, bridging effects of spacers, and edge).

Another promising means to reduce conductive/convective and radiative heat transfer through a glazing system is to fill the space between a double glazed window with a transparent insulating material. Silica aerogel is such a material and is currently under development for use in widows (Hunt 1991). Because the silica particles which comprise the microporous material

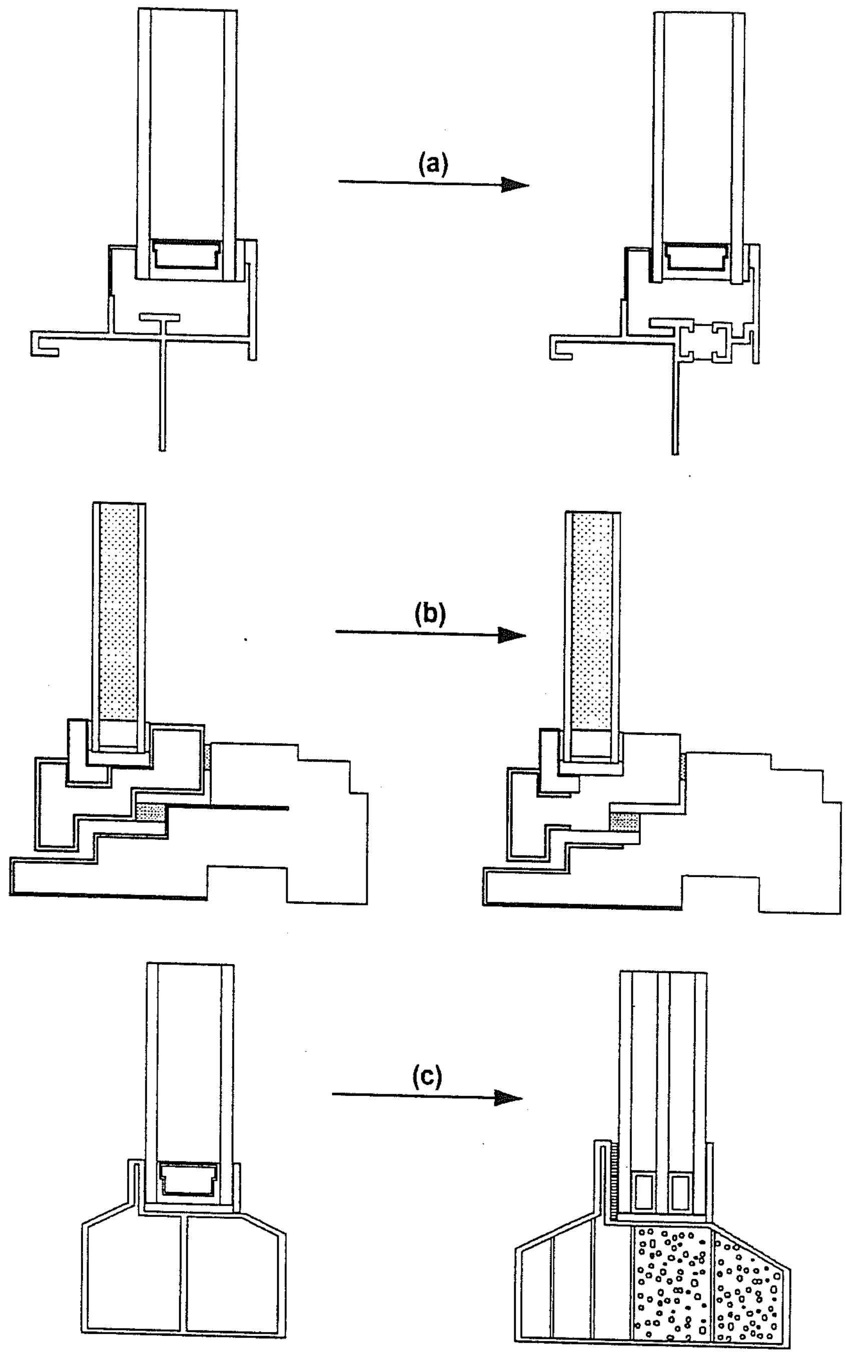


Figure 7.14: Typical window frames can be redesigned for improved thermal performance. A typical aluminum frame (a) has a thermal break added to it. A typical aluminum clad wood frame (b) has reduced cladding on the exterior. A typical vinyl frame (c) uses smaller cavities, some of which may be foam-filled.

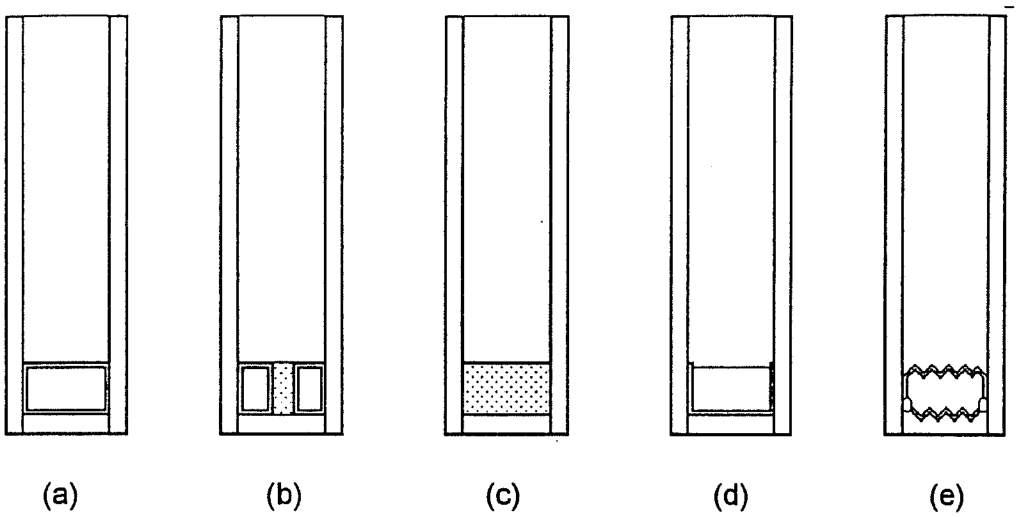


Figure 7.15: Typical aluminum window spacers (a) have been redesigned for improved thermal performance. Options include thermally broken metal (b), foam or butyl spacers (c), U-shaped spacers (d), or spacers made of stainless steel with a longer path length (e).

are much smaller than the wavelengths of visible light, silica aerogel is transparent to the human eye. With approximately 95% of the air by volume in aerogel contained in pores smaller than the mean free path of air molecules, the thermal conductivity of aerogel will be lower than that of air. Measurements on the thermal conductivity of aerogel, see Fig. 7.18, confirm this (Hunt 1992). Note that aerogel in a soft vacuum is an excellent insulator; sealing a window against this soft vacuum is a much more forgiving task than against a hard vacuum. Evacuated aerogel windows also act as their own transparent spacers since aerogel has enough compressive strength to balance the external atmospheric pressure. Since aerogel is opaque to most long-wave infrared radiation, net radiative losses through an aerogel window are minimal. Recent aerogel research has focused on the cost-effective production of large aerogel samples with minimal haze and their incorporation into durable insulating glass units. Fig. 7.19 is a photo of an aerogel window.

Various transparent or translucent insulating materials (TIMs) have been developed or are the subject of current research (primarily in Europe) for use in non-view building envelope applications. TIMs can be used to provide light or solar gains to spaces which already have view windows. As shown in Fig. 7.20, we can define four types of TIMs:

- Slat Structures

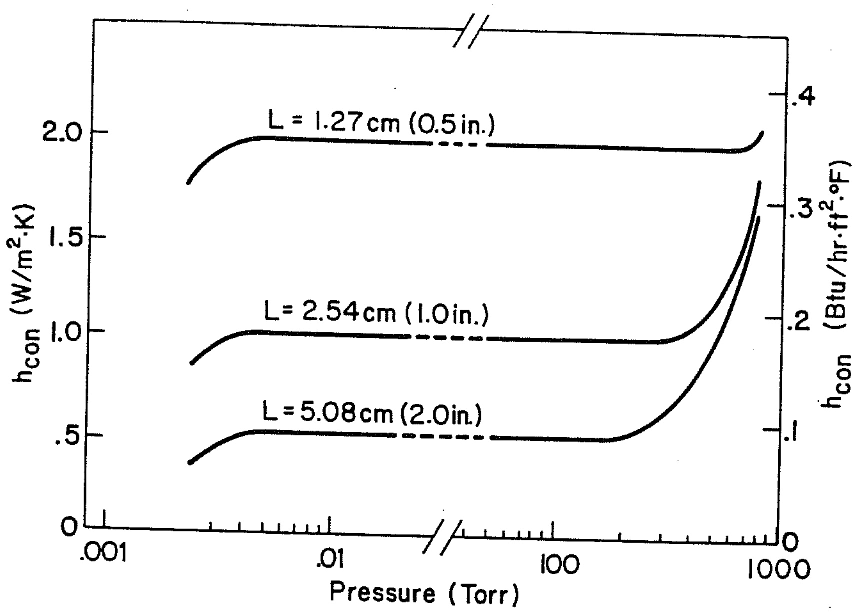


Figure 7.16: The air-gap conductance for an evacuated window as a function of the pressure within the gap.

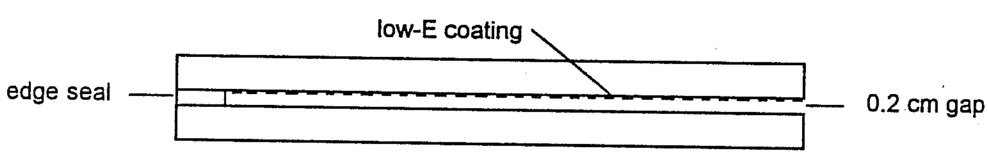


Figure 7.17: Schematic of an evacuated window.

- Parallel Plate Structures
- Cavity Structures
- Quasi-Homogeneous Structures.

TIMs typically have thermal properties on the order of conventional opaque insulations and are thicker than conventional insulating glass units, thereby providing a significant resistance to heat transfer. Optical properties are also different than conventional insulating glass units, with incident solar radiation often being scattered on its way through the TIM. As a result, measuring the optical properties of TIMs can be challenging.

TIMs are not intended to replace conventional view windows; rather they are intended to be used as a novel building material. Since their

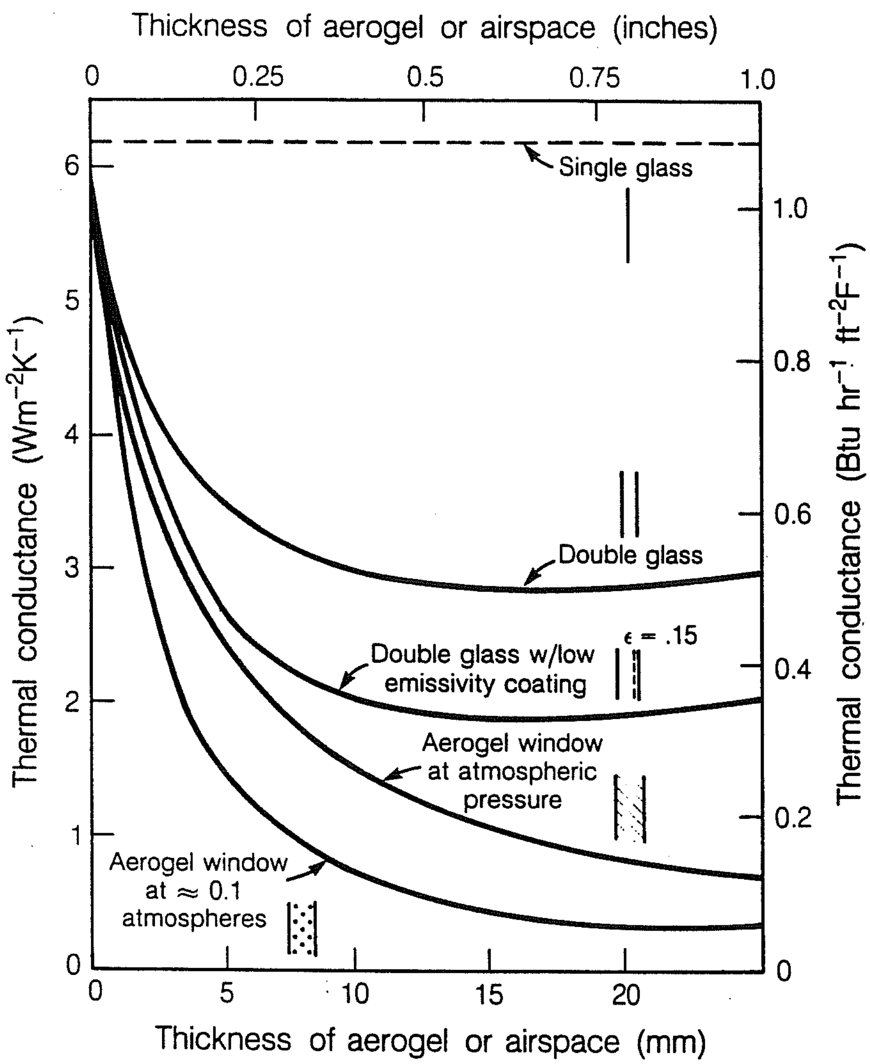


Figure 7.18: Thermal conductance of aerogel windows as a function of thickness and pressure.

thermal conductances are often equivalent to those of a wall, their use as a source of daylight in areas where insulated walls would typically be used is appropriate. TIMs are also appropriate for use in various types of solar collectors and in Trombe wall type applications. In Europe, where there is a large stock of uninsulated masonry buildings, TIMs coupled with a solar

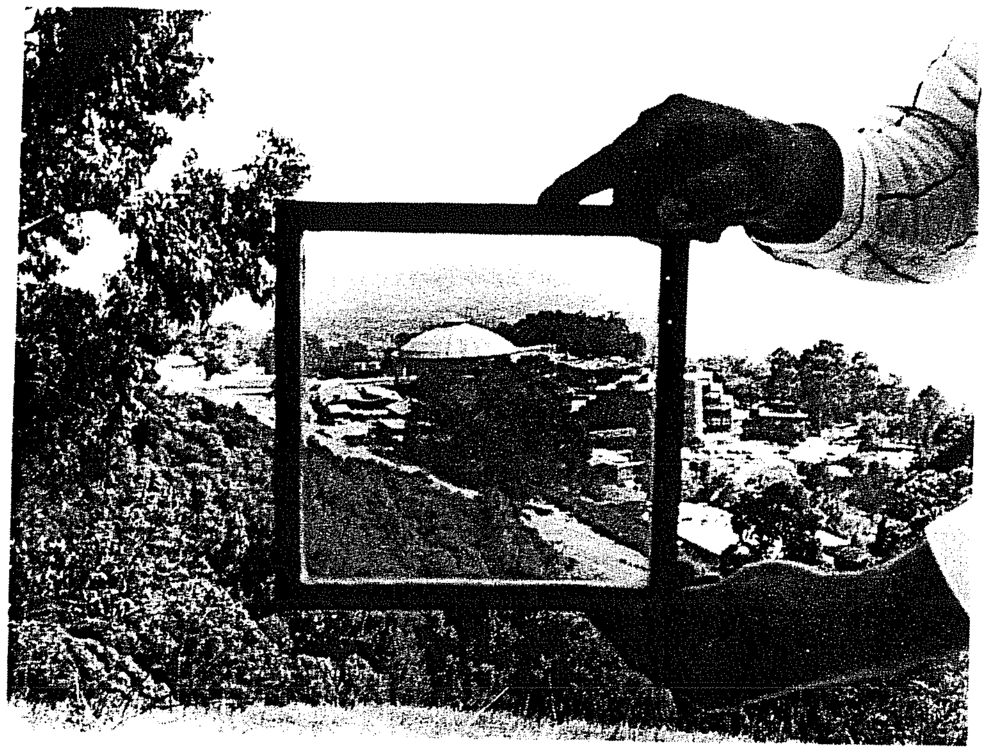


Figure 7.19: An aerogel window.

control mechanism, could be an excellent retrofit technology (Lampert 1992, Wittwer 1990, Chahroudi 1991).

7.5 Technological Advances in Controlling Window Solar Heat Gains

Solar heat gains through windows can either contribute positively or negatively towards a building's energy efficiency. The impact of solar gains will vary with building type and use, climate, season, and even time of day. Unlike window U-values, where lower U-values are almost always better, there is not a universal goal for Solar Heat Gain Coefficients. For some applications, SHGCs should be maximized, for others, SHGCs should be minimized. Controlling solar heat gain is also related to other human comfort factors (i.e. thermal and visual comfort and uv fading). Often, as with the case of direct solar radiation, visual comfort concerns will dominate over the need for solar gains.

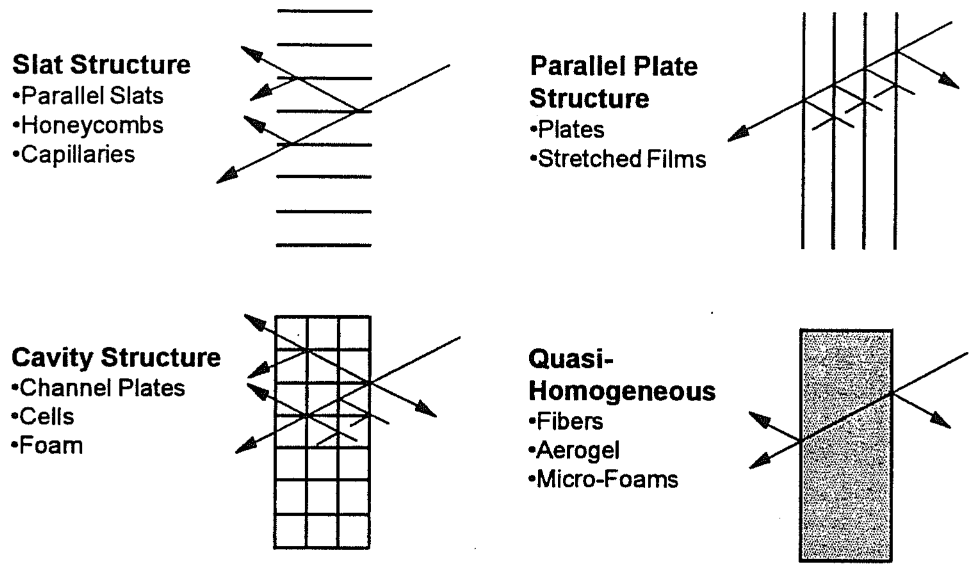


Figure 7.20: Four types of transparent insulating materials (TIMs).

7.5.1 Maximizing Solar Heat Gains

In some applications, typically residential heating dominated situations, it is important to maximize the solar transmission through window systems. Clear glass, with a solar transmittance of 0.84 for 3mm thick glass and of 0.78 for 6mm thick glass, has a reasonably high solar transmittance. Higher transmission rates can be obtained by minimizing the impurities in the glass mixture (low-iron glass). When low-e coatings first appeared on the market in the mid-1980s, the coatings typically reduced solar gains; since then, coatings have been developed which are better able to maintain the solar transmittance characteristics of uncoated glass. Table 7.4 gives the solar transmittances of typical uncoated and low-e coated glazings. This paper does not cover focusing or concentrating systems designed to increase the amount of radiation incident on an aperture.

7.5.2 Controlling Solar Heat Gains

The control of solar heat gains are of significant concern to the designer of an energy-efficient building for the following reasons:

- More and more residences are being built with air-conditioners; in many northern climates, reasonably insulated homes will have cooling costs similar to heating costs. Note that electricity costs are typically much higher than heating costs, especially in newer gas-heated homes.

Table 7.4: Solar Transmittance of Typical Uncoated and Low-e Coated Glazings

	Layer Solar Transmittance
3mm clear glass, uncoated	0.85
3mm clear, sputter coated low-e	0.65-0.70
3mm clear, pyrolitic deposited low-e	0.75

- Virtually all commercial buildings in most US climates are cooling dominated; solar gains through the exterior envelope are a large contributor to the cooling load.
- Cooling loads are most significant on hot summer afternoons when electric utilities typically have their annual peak load demands. Lower solar heat gains lead to lower peaks which lower peak demand charges.

There are three ways in which solar heat gains need to be controlled:

· by intensity
· by variations in time
· by spatial distribution.

7.5.2A Controlling Solar Heat Gain Intensity

Historically, the need for the control of solar gains increased as the popularity of the modern commercial building increased. Beginning in the 1940's, solar gains began to be controlled through the use of tinted (sometimes called heat absorbing) glass and, starting in the 1960's, through the use of reflective glass.

While both tinted and reflective glass products are effective at reducing solar gains, the means they use to reduce solar gains were somewhat arbitrary. Fig. 7.21 shows transmittance curves as a function of wavelength, over the solar spectrum, for common tinted and reflective glass products. Also shown is a graph of solar spectral irradiance as a function of wavelength. Note that approximately half of the incident solar energy is in the solar infrared; this solar radiation should be the first to be rejected by a solar control glazing since it does not provide any contribution for daylighting a space. If further reductions in solar heat gain are necessary, the transmittance across the visible portion of the solar spectrum can be reduced.

In the late 1980's, manufacturers of sputtered low-emissivity coatings realized that they could alter the point at which their coatings shift from transmitting to reflecting. Fig. 7.22 shows the solar transmittance of a low-e coating originally designed to maximize solar transmission for a residential heating dominated application. Also shown is the same product, re-designed

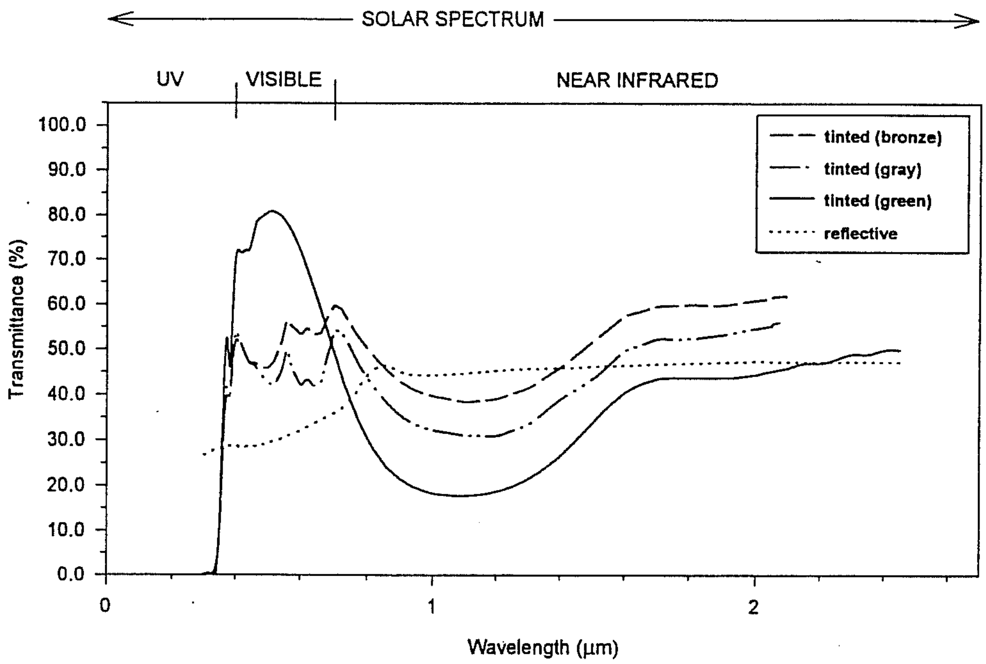


Figure 7.21: Transmittance curves for common tinted and reflective glasses.

to minimize solar heat gains while maximizing visible transmission and color neutrality. Such second generation low-e coatings are often generically called spectrally selective coatings since they are selective in the solar spectrum (Schumann 1992). Insulating glass units built with such coatings can have visible transmittances significantly higher than their conventional counterparts (see Fig. 7.23).

Another approach to creating a spectrally selective glazing layer is to tint the glazing with a material which absorbs in the solar infrared. Several such products are commercially available today. Because the absorbed solar radiation can flow inwards, such products are most effective when used as the outer layer in a double glazed low-e unit (or higher performing unit).

Controlling solar gains can also be achieved through the proper design of insulating glass units. Units which are designed to limit heat gain by absorption (as opposed to reflection) should have the absorbing layer placed in as much thermal contact with the exterior as possible so that the inward flowing fraction of the absorbed component is low. Absorbing layers should thus be placed on the exterior and the thermal resistance between the absorbing layer and the interior space should be as high as possible (i.e. through the use of a low-e coating and a gas-fills).

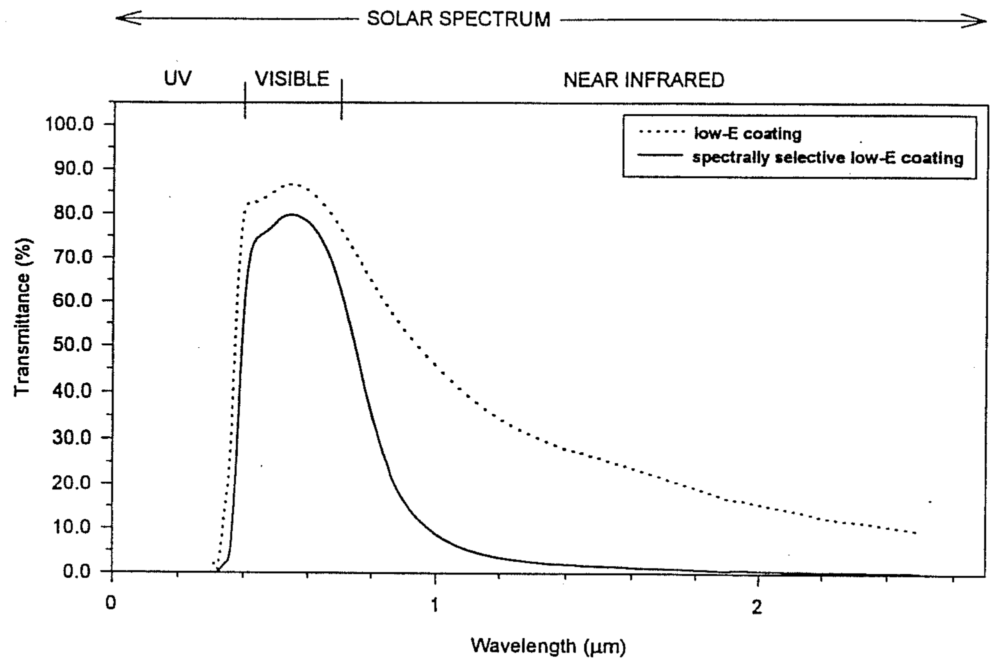


Figure 7.22: Transmittance curves for a first generation (heating climate) low-emissivity coating and a spectrally-selective (cooling climate) low-e coating.

7.5.2B Controlling Solar Heat Gain Variations in time

In many applications, it may be advantageous to use a glazing system with time dependent solar-optical properties. Such situations focus on commercial applications where the benefits of solar gains and daylight will vary on a daily or hourly basis but can also include residential applications where the desirability of solar gains vary on a seasonal basis. Such functions have typically been covered by shading systems; however, optical coatings offer the potentials for more comprehensive, effective, and efficient solutions. Glazings with variable properties are typically called chromogenic (switchable) glazings or smart windows. While chromogenic glazings offer a significant opportunity for increased energy benefits, they are just beginning to become commercialized.

The primary focus of research efforts in this field has been to produce glazings which control the intensity of transmitted solar gains and daylight. Such systems could be used in commercial buildings to provide an optimum amount of daylight with minimal adverse effects, thereby reducing the energy and peak demands imposed on buildings by electric lighting (Johnson 1985, Warner 1992). Since daylight is "free," and since it is typically a more

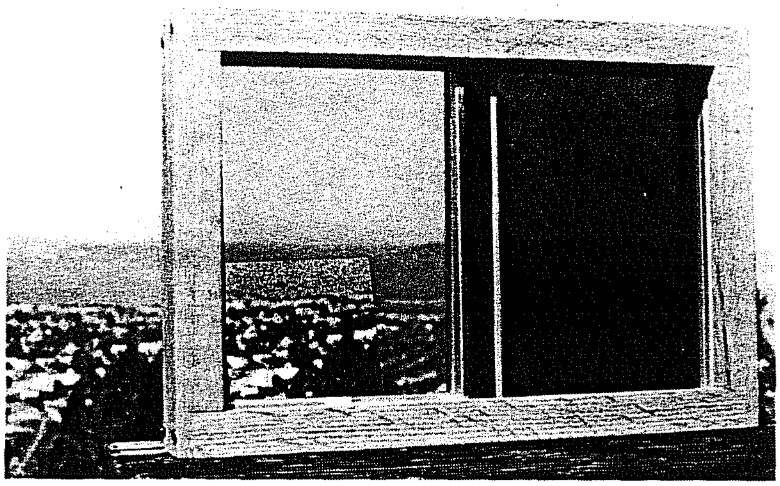


Figure 7.23: These two glazings both have the same Shading Coefficient; however the spectrally selective glazing on the left lets in approximately four times as much visible light as the commonly used gray tinted glazing on the right.

efficient source of light than electric lights (see Fig. 7.24), it is advantageous to use daylighting as much as possible to provide the necessary illumination in spaces. However, the transmission of too much daylight can increase cooling loads dramatically; thus the need for switchable glazings.

While there are several different types of switchable glazings, they all have several features in common. All switchable glazings are activated by a physical phenomena (light, heat, electricity). Once activated, they switch, either incrementally or completely, to a different state. The state with the highest solar transmittance (typically the unactivated state) is called the bleached state and the state with the lowest solar transmittance is called the colored state.

Three control mechanisms exist. These are photochromic (or light sensitive), thermochromic (or heat sensitive), and electrochromic (electrically activated) systems. Each control strategy will have different effects on the building's thermal patterns. For example, photochromic glazings may be appropriate for the control of daylight; however, they are insensitive to solar heat gain effects. Thermochromics can respond well to thermal effects, but may not necessarily allow the proper transmittance of daylight and may not be able to distinguish between high ambient temperatures vs. incident solar radiation. Electrochromics offer the greatest potential for energy savings since their control can be integrated into total building energy management

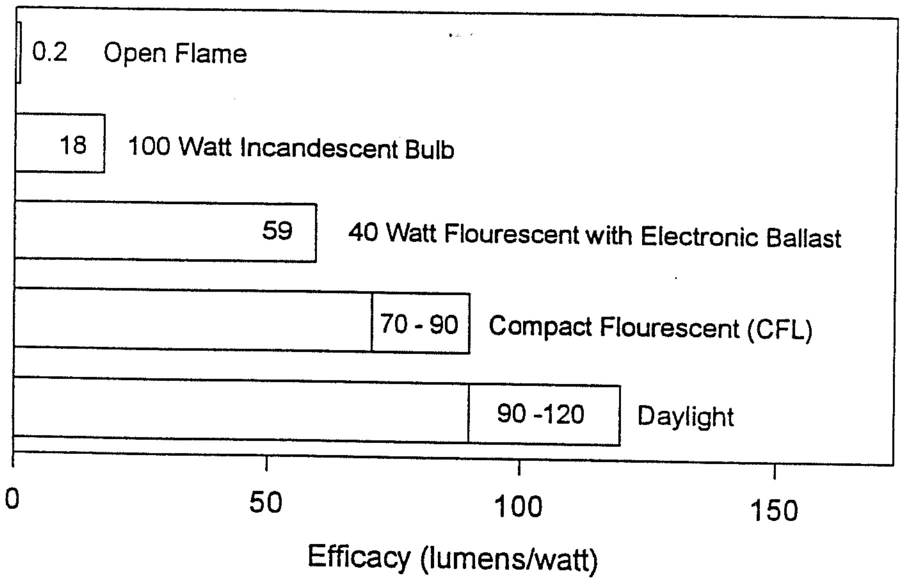


Figure 7.24: Natural daylight produces the most amount of visible light for the least heat.

systems, optimizing the tradeoffs between lighting energy and cooling consumption.

Photochromic materials alter their optical properties when exposed to light, typically UV, and revert to their original state when the light is removed. This phenomenon is widespread, occurring in organic and inorganic materials. Probably the most widespread use of photochromic materials in consumer goods is for sunglasses. Since this photochromic glass cannot as yet be produced using the float glass process, it would be prohibitively expensive to be used in building applications. Current research is aimed at developing photochromic plastic layers; as yet these have not exhibited the necessary durability (Lampert 1992).

Thermochromic materials show a change in optical properties when subjected to a change in temperature. Thermochromism is seen in both organic and inorganic materials with the primary commercial interest to date in inks, paints, security devices, temperature indicators, and even clothes. Criteria for the development of a suitable thermochromic for window applications include durability, switching or activation temperatures, switching range (intensities and wavelengths), and optical clarity in the colored state. Suntek Co. of Albuquerque NM has developed a thermochromic polymer

(Cloud Gel^{TM}) which becomes diffuse in the bleached state; this product is currently undergoing demonstration and durability testing (Lampert 1992).

Electrochromic glazings are complex multi-layer coatings whose optical properties vary continuously from a highly transmissive or bleached state to a low transmitting or colored state. A small potential difference, typically 1-5 volts, is all that is required to trigger a change in state. The longer the potential difference is applied, the more the electrochromic layer will switch, until it reaches its maximum or minimum. A schematic diagram of an electrochromic is shown in Fig. 7.25 (Lampert 1992, Selkowitz 1990). Electrochromics can be tied into building energy management control systems, thereby allowing the glazings to be controlled by a predefined algorithm which best suits each application. For this reason, electrochromics are viewed as having a greater potential for energy savings and user comfort than photochromics or thermochromics.

Currently, glass companies and research organizations throughout the world are working to commercialize electrochromic technology (see Fig. 7.26). Much of this research is proprietary, although sample electrochromics are on display in Japan. A U.S. manufacturer has developed an electrochromic for use in automobile rear-view mirrors which is controlled by a photo-sensor. Several manufacturers offer liquid-crystal devices which change from a low-transmitting translucent state to a transparent high transmission state. Because of the large and continuous voltage required to keep these devices in the clear state, they are typically not energy-efficient products; their primary purpose is as privacy screens in offices, limousines, etc.

It is important to note that it is not necessary to optimize the properties of the electrochromic glazing but rather to optimize the properties of the glazing system or window which incorporates an electrochromic layer. Since electrochromics, in their colored state, are intended to minimize solar gains, it is important that the solar gains not directly transmitted make their way to the exterior of the building. The best way to accomplish this is to use an electrochromic layer which switches from transmitting to reflecting. However, such a requirement is a limiting factor in the development of electrochromics. Another alternative would be to use an electrochromic device which switches from transmitting to absorbing and is placed in the IG unit in such a way that the inward flowing fraction of the absorbed component is low (Reilly 1991). Note that the use of an absorbing layer may require the use of heat strengthened or laminated glass. Different electrochromic devices may also have different spectral responses. In commercial buildings, the primary target application for electrochromics, solar gains outside the visible portion of the spectrum should be excluded virtually all the time. Therefore, an electrochromic layer can either be designed to reflect the solar

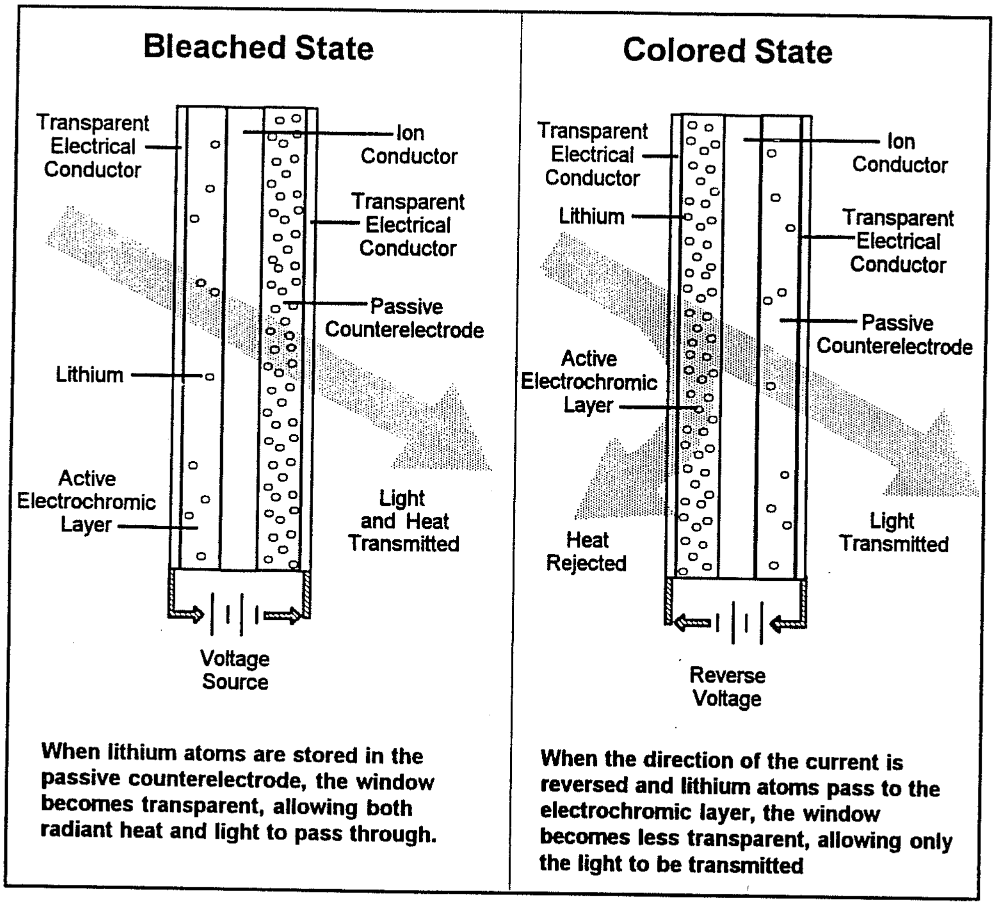


Figure 7.25: Schematic cross-section of an electrochromic glazing.

infrared with modulating transmittance properties over the visible portion of the solar spectrum, or it can be designed to be used in conjunction with a spectrally selective glazing layer (see Section 7.5.2) with the only requirement on its switching capabilities being in the visible portion of the solar spectrum.

7.5.2C Controlling Solar Heat Gain Distribution

In a daylighted commercial building, there is often a surplus of daylight; unfortunately it is typically not distributed evenly throughout the floor space. While skylights are an effective means to daylight a building, their use is limited to the top floor of a building. As a result, other approaches must be explored to redistribute daylight incident on the side of a building

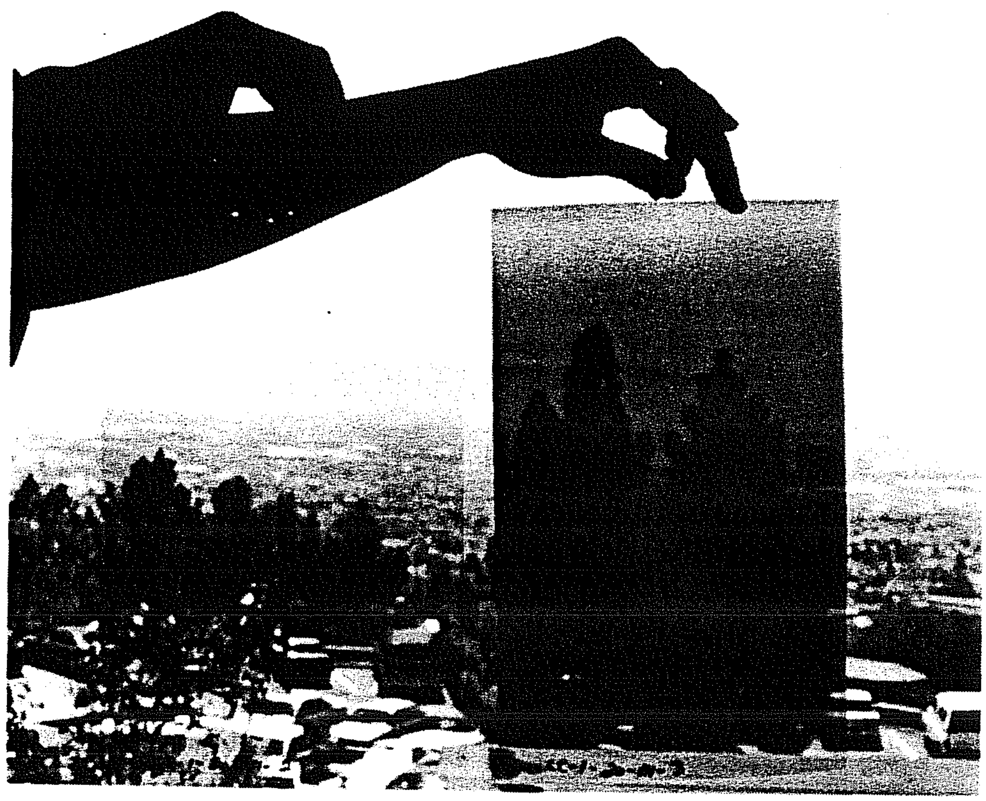


Figure 7.26: Two samples of a prototype electrochromic. The sample of the left is in the bleached or highly transmitting state. The sample on the right is in the colored or low transmitting state. This material can also be quickly reset to any state in between.

to areas closer to the center of the building. There are two approaches to this task, either modify the glazing or add an element directly inside and/or outside of the glazing to redistribute the daylight.

Developing glazings which redirect incoming solar radiation is the subject of ongoing research. Two classes of technologies are being pursued, holographic (Papamichael 1993) and angular selective glazings (Lampert 1992).

Light shelves and more complex light pipes are physical elements added to the skin of a building and/or to the interior. While they can be more complex, light shelves are often simple horizontal elements, running continuously around a building. Fig. 7.27 shows the daylighting distribution for

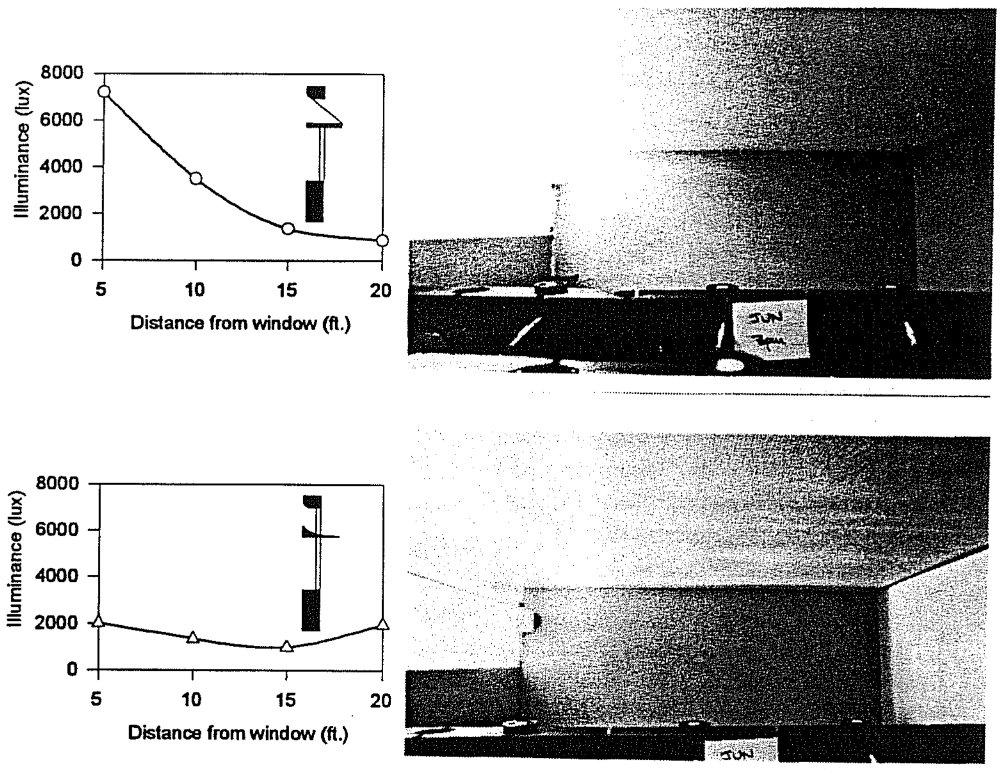


Figure 7.27: Daylight distribution for a typical sidelighted space (top) and for the same space retrofitted with an engineered light-shelf (bottom). The addition of the light shelf improves the daylight distribution within the space, as shown in the graphs above.

conventional and advanced light shelves. Light pipes are more defined, rectangular "pipes" extending inward into the building. Fig. 7.28 shows schematics of both light shelves and light pipes. Other designs are certainly possible and could be integrated into the structure and architecture of a building.

7.6 Fully Integrated Windows

Energy conservation features of windows in both residential and commercial buildings are hampered by the fact that windows are often thought of as independent components of a building. By thinking of windows as one element of a building system, further energy savings are possible.

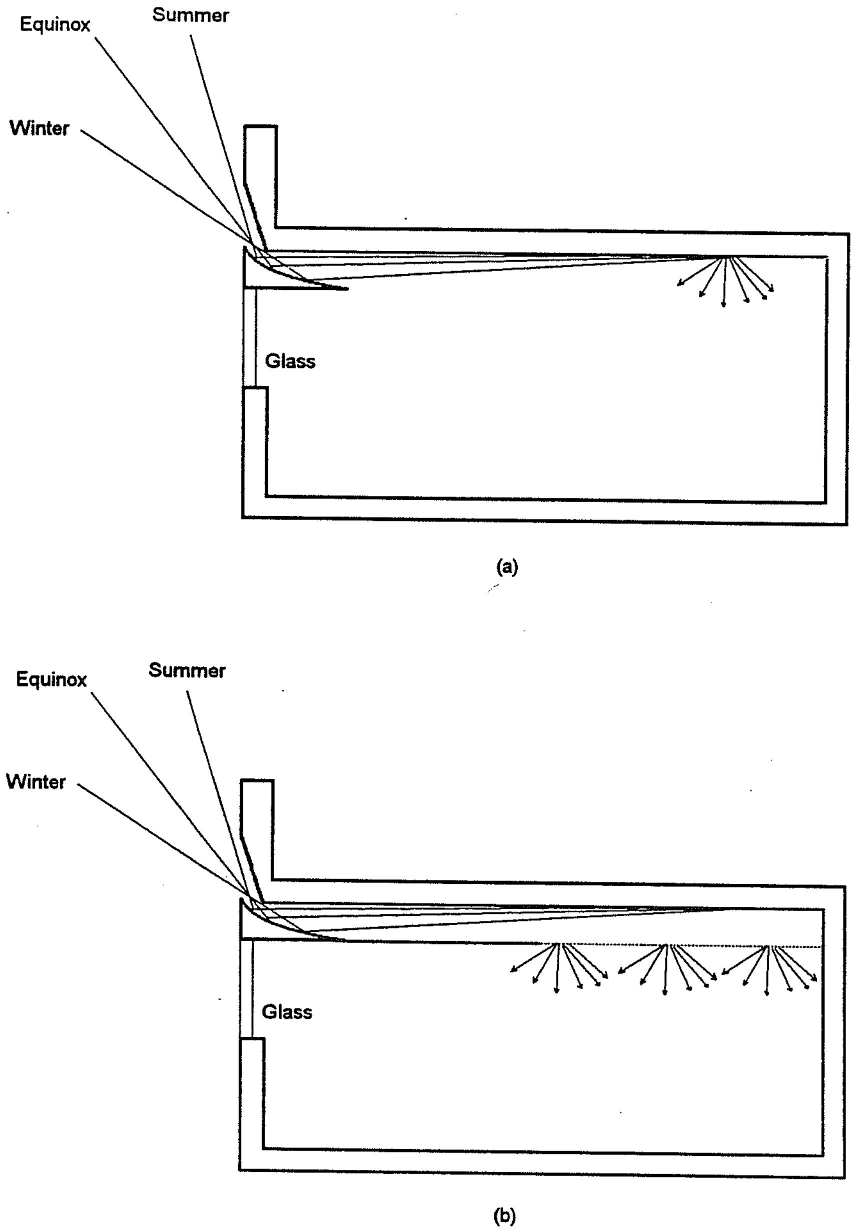
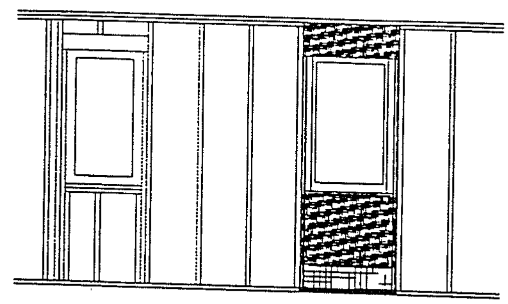


Figure 7.28: Schematics of a light shelf (a) and a light pipe (b). The light shelf tends to focus light on a particular area while the light pipe gives a more uniform and diffuse light distribution.

Integrated Window Systems Used with Conventional Framing

- Top Plate and Sheathing Cover Joints
- Matches Undisrupted Stud Layout
- Nail or Screw to Neighboring Stud
- No Headers, No Window Installation



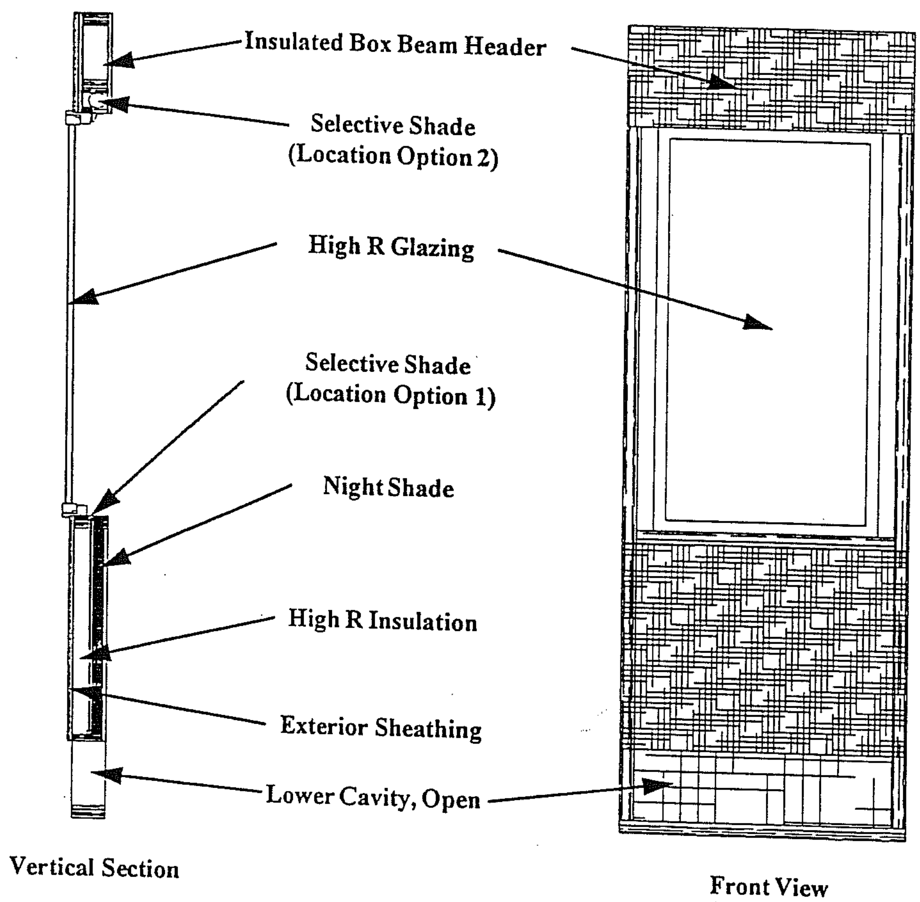


Figure 7.29: An Integrated Window System improves the thermal performance of the wall space surrounding a window and allows the wall to be used to improve the thermal performance of the window.

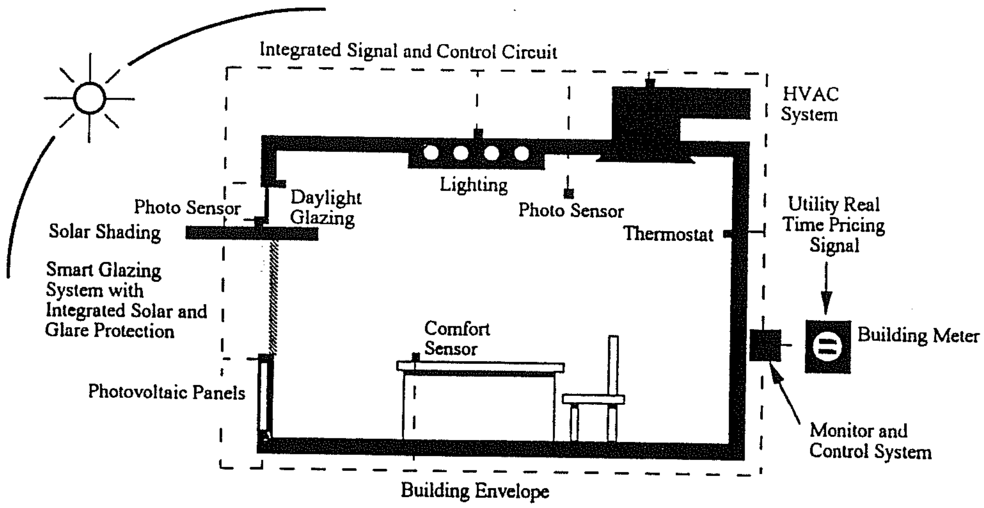


Figure 7.30: This schematic of an integrated commercial building shows how the glazing is optimized to provide as much daylight as possible without admitting excessive solar gains. The envelope, lighting, and HVAC systems are all aware of each others demands and their operation is centrally controlled.

7.6.1 Residential Applications

The concept of an Integrated Window System (IWS), a window wall panel designed to be built in a factory and efficiently integrated into conventional stick-built construction, offers additional energy savings potentials for residential applications. Such panels would be pre-engineered to handle structural loads and would entirely replace typical framing components (see Fig. 7.29) Key components of an IWS panel include:

- movable interior insulating night shades recessed into the wall cavity,
- seasonally deployed solar shading,
- optional overhangs,
- insulated box beam headers,
- larger glazed areas.

At the time of this writing, IWS prototypes are being designed (Arasteh 1994).

7.6.2 Commercial Applications

It is even more imperative that glazings in commercial buildings be thought of as parts of a larger system than in residential applications. Glazings and the exterior envelope design, lighting systems, and HVAC equipment are all typically specified and installed separately. However, for the true potentials of advanced products (such as elctrochromics or lightshelves) to be realized, links to other building energy systems must be understood. Fig. 7.30 illustrates this concept (Lee 1993).

7.7 Summary

Through a comprehensive understanding of heat transfer and optics through window and other fenestration systems, manufacturers can design more energy-efficient fenestration products. By better understanding the energy impacts of fenestration technologies in a space, building designers can make more efficient use of advanced fenestration technologies.

Technological advances over the past twenty years include the development of low-emissivity coatings aimed at reducing long-wave radiant heat transfer and/or transmission of the near-infrared portion of the incident solar spectrum. The use of low-conductivity gas-fills to minimize conductive/convective heat transfer, thermally broken spacers, and insulating frames have all helped to increase the overall thermal resistance of fenestration products.

Technologies under development include more advanced insulation technologies such as aerogels, evacuated windows and transparent insulating materials (TIMs). Switchable glazing technologies, which allow for the time-dependent transmittance of solar radiation, are the focus of international research efforts. Finally, as fenestration technologies become more advanced, it is imperative that their use in buildings be integrated with other building elements in both the design/specification and installation stages.

7.8 Acknowledgments

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technologies, Building Systems and Materials Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. The author wishes to acknowledge the contributions of his colleagues at the Windows and Daylighting Group at Lawrence Berkeley Laboratory and in particular, to Fredric Beck for his invaluable assistance in preparing figures.

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